ARTICULATORY CHARACTERISTICS OF SIBILANT PRODUCTION IN YOUNG PEOPLE WITH DOWN'S SYNDROME

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Abstract

Speech production in children with Down's syndrome (DS) has been found to be variable and inconsistent. Errors are concentrated in consonants that are typically late developing, such as fricatives. It has been suggested that inconsistency in speech production in DS is a result of a motor speech deficit but there is little detailed articulatory evidence to support this claim.

This study (with data from MRC grant 'Assessment and Treatment of Impaired Speech Motor Control in Children with Down's syndrome' (G0401388)) provides a detailed phonetic analysis of the voiceless sibilants /s/ and /ʃ/, in a group of young people with DS, by means of auditory and articulatory analysis. The aim of the study is to assess fine motor ability and articulation variability at word level production in a group of speakers with well-established difficulties in speech articulation.

The study analysed data from 25 children with DS, 10 typically developing children and 8 adult speakers, recorded using EPG. Perceptual measures were compared with quantitative analyses of EPG data, along with visual analysis of articulation patterns based on a new set of articulation taxonomies. The data is presented by group and in the form of 5 case studies. The case studies provide a means to analyse the relationship between articulation and auditory information in detail and to compare these with supplementary motor control measures.

The results show presence of atypical articulation patterns for speakers with DS for both perceptually acceptable tokens, and those in error. Higher levels of within-speaker articulation variability are presented in comparison to the TD control group. Further findings suggest presence of articulation patterns in the TD speakers previously unidentified in EPG studies.

Similar to previous studies, the results find that speakers with DS are a highly variable group and that speakers display a combination of typical and atypical speech patterns, influenced by speech motor control difficulties.

Keywords: Down's syndrome, Electropalatography, sibilants, speech motor control, atypical speech articulation

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'Hey, hey, hey, the end is near

On a good day you can see the end from here

But I won't turn back now though the way is clear

I will stay for the remainder'

Joanna Newsom – On a Good Day

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DS	Down’s syndrome
TD	Typically Developing
AD	Adult
PCC	Percent Consonants Correct
PVC	Percent Vowels Correct
PTA	Percent Target Consonants Acceptable
OSVar	Overall Spatial Variability
PSVar	Perceptually Acceptable Spatial Variability
CA	Canonical Analysis
COV	Coefficient of Variation
WTM	Whole Total Contact Measure
COG	Centre of Gravity
CAS	Childhood Apraxia of Speech
QMU	Queen Margaret University
MRC	Medical Research Council

1. Introduction

Down's syndrome (DS) is a genetic disorder caused by the presence of an extra chromosome in the 21st pair. It is the most common genetic disorder for intellectual disability. In England and Wales in 2011 there were an estimated 725 Down syndrome's live births (a rate of 1 in 1000 live births) (NDSCR 2011 Annual Report). These genetic differences result in a number of neurological, physical and cognitive deficiencies, many of which can affect speech and language development. Abilities vary with some areas (social adaptation, visual skills) less delayed than others, in particular language ability (Hodapp, Burack & Zigler, 1990). Significant problems with speech intelligibility (Kumin, 1994) have been continuously identified in people with DS. In a parental survey of 934 respondents, Kumin (1994) reported that 58% said their child was frequently misunderstood. A further look at the data found that for the majority of the respondents (parents of children 0-21yrs) 74-85% noted problems with articulation. Articulation is considered problematic for people with DS, with difficulties often found with the later developing consonant sounds.

A combination of motor control difficulties, anatomical and structural differences and hearing loss may contribute to the articulation problems exhibited by people with DS (Rondal, 2009) but these differences do not fully account for the severity of speech problems found in this population (Laws & Bishop, 2004). The prominence of these difficulties have led many researchers to query the nature of the speech problems in DS, with studies noting high levels of delayed phonological development and therefore concluding a delayed developmental pattern of speech production. However, studies also present evidence of variability in speech articulation and presence of atypical errors, suggesting a more atypical developmental pattern. Although studies often claim presence of atypical speech activity in this group, very little detail is provided of the nature of these atypical errors.

The reporting of atypical speech production in children with DS may be lacking as investigations are often limited to phonological analyses, with only a few assessing speech articulation via instrumental techniques. Some acoustic studies exist, though these are primarily interested in vowel production (Bunton & Leddy, 2011; Moran, 1986; Pentz, 1987; Whitworth & Bray, 2015), with a small amount investigating the nature of consonant production (Brown-Sweeney & Smith, 1997; Callahan-Mandulak et al., 2006). It is suggested that further investigation using instrumental analysis techniques (e.g. articulatory analysis) is required to fully understand the nature of speech production difficulties in this population.

Moreover, although often claimed to contribute to articulation problems, there is little knowledge of speech motor abilities in this group of speakers. While evidence exists to support the presence of oral-motor difficulties in this group (Spender et al., 1995), information regarding actual speech motor behaviour is still under-represented.

It is therefore proposed that investigating the nature of speech production in DS could be achieved by using the articulatory technique, Electropalatography (EPG). EPG can provide a fine level of detail regarding tongue-to-palate contact and articulation variability which may provide evidence of articulatory patterns not reported in the literature to date. Furthermore, the particular speech motor functioning problems in DS can be investigated through identification of atypical tongue placement patterns or inconsistency measures, both measures provided by EPG with potential to investigate motor speech abilities (McAuliffe, Ward & Murdoch, 2002). Additionally, EPG articulatory information can provide data to inform and guide speech intervention planning in this population.

The main motivation for this thesis was to further investigate whether detailed articulation information could provide evidence of atypical speech errors that may be related to speech motor difficulties. Evidence suggests that children with DS present with typical (yet delayed), and also atypical speech production. To date, there is very little articulatory information for children with DS, unlike the large volume of work with cleft palate and functional articulation disorders. Previous EPG studies (Hamilton, 1993; Gibbon, McNeil, Wood, & Watson, 2003) have presented on small groups of speakers and have identified presence of atypical articulation errors. This present study intends to expand on these studies by using EPG to investigate the production of speech sounds commonly produced in error (voiceless sibilant fricatives). By analysing these speech sounds in cognitively age-matched typically developing children and children with DS, this will provide a means to investigate whether children with DS present articulatory errors patterns similar to TD children or not.

In particular this investigation presents detailed articulatory analysis of the commonly misarticulated speech sounds /s/ and /ʃ/, in a group of 25 children with DS. Results were compared to two control groups, typically developing children and adults, providing comparisons with a fully mature speech sound system and an immature, still developing, sound system. This research presents the first detailed articulatory study of complex speech sounds in children with DS using EPG.

Chapter 2 provides background information on DS and specifically the speech problems found in the literature. This is followed by a detailed look at the sibilant fricatives /s/ and /ʃ/, and their behaviour in typical and disordered speech populations. At this point, particular aspects of DS are considered and their impact on successful production of these two sounds. The articulatory analysis technique Electropalatography (EPG) is then reviewed in this chapter with particular focus on studies that have analysed typical and disordered fricatives. The research questions and hypotheses will be presented at the end of this chapter.

Chapter 3 will present the first part of the methodology, which provides an explanation about the context of the PhD study within a funded research project. The chapter provides information on the participants, the data collected and the analyses techniques employed. Chapter 4 continues the methodology but presents detail of the descriptive EPG analysis; involving a categorisation based on the EPG speech data.

The results are presented in three separate chapters. Chapter 5 will present the perceptual and quantitative EPG measurement results. Chapter 6 will present results from the descriptive analysis of EPG data and finally, Chapter 7 will present results from five case studies.

The thesis concludes in Chapter 8 with a discussion and interpretation of the results and their relationship to previous and current work in the field. The chapter concludes with suggestions for future research and a summary of the main findings.

2. Background

2.1 **Introduction**

This chapter will provide information on speech production in Down's syndrome (DS) alongside the etiological and associated factors that may negatively impact success in this area, drawing particular attention to speech motor difficulties. A review of speech production in DS will be presented. As will be seen from the literature reviewed below, sibilant fricatives are commonly produced in error in this group and as such have been selected for detailed investigation. Therefore, section 2.4 will present a detailed look at the articulation of sibilant fricatives in typically developing children and individuals with DS, along with a focussed section that considers the particular difficulties that may impact on successful sibilant production in speakers with DS. This will then lead into a review and explanation of the benefits of the Electropalatography (EPG) technique in analysing these difficult speech sounds, concluding with a review of EPG studies in individuals with DS to date.

2.2 **Down's syndrome and factors associated with speech difficulties**

DS is a genetic disorder resulting from chromosomal abnormalities. There are three types of abnormality that give rise to DS (Trisomy 21, Translocation and Mosaicism). Trisomy 21 is the most common and is the result of an extra chromosome in the 21st pair. The presence of this extra chromosome causes anatomical, structural, neurological and cognitive differences. It is well established that people with DS present with a variety of phenotypes (Korenberg et al., 1994 Chapman & Hesketh, 2000; Roper & Reeves, 2006) and not all identified features of DS occur in the whole population. Generally people with DS can display low levels of intelligence and a distinct physical profile, particularly in the craniofacial skeleton, and are easily identified by the presence of a flattened nasal bridge, flattened mid-facial region, small jaw and oral cavity, lowered lip and protruding tongue, reduction in ear size (Sforza, Dellavia, Zanotti, Tartaglia & Ferrario, 2004). Korenberg et al. (1994) note that nearly 100% of people with DS have low cognitive abilities and muscle hypotonia. Further differences are noted by Fidler, Most and Philofsky

(2008) who suggest a primary phenotype of DS (one that is directly related to the genetic and biological structure of DS) is the motor and articulatory deficits in language production. These articulation difficulties are well noted in the literature with research often investigating the origins of problems. For example, Fidler et al. (2008) relate the articulatory deficits in DS to oral cavity differences (though they do not provide any evidence for this link). Other aspects of DS that have been related to the problems in speech production in this population are muscle hypotonicity (particularly weak facial muscles, lips and tongue), motor control and motor planning difficulties, hearing loss and anatomical differences (Miller & Leddy 1998; Rondal & Edwards, 1997; Spender et al., 1995). Although children with DS present with low cognitive abilities, research suggests that this is not related to speech production difficulties (Cleland et al. 2010), suggesting that either some, or all of the above mentioned aspects of DS have an impact on successful articulation.

2.2.1 Neurology

Motor difficulties in people with DS have been related to the smaller than average cerebellum, affecting the coordination of facial muscles (Latash, Kang & Patterson, 2002; Wishart, 1998) which (as will be discussed in 2.4.8) will affect the ability to control and maintain articulators during speech production. Overall, the brain in people with DS is smaller than normal, but particularly the cerebellum, which has been considered disproportionately smaller than age-matched TD speakers (Pinter, Eliez, Schmitt, Capone & Reiss, 2001). Aside from neuroanatomical difficulties, Pinter et al. (2001) found preservation of many sub-cortical and parietal areas (particularly the areas related to visual-spatial skills). However, differences have also been identified with the corpus callosum (fibres that connect the right and left hemispheres of the cerebrum) which has been found to be incomplete in DS (which can affect transfer of information across the hemispheres) (Wang, Docherty, Hesselink, & Bellugi, 1992). In addition, a few listening studies have found that along with differences in size, people with DS show reverse hemispherical organisation for speech perception, with the right hemisphere containing the cortical areas for this function (though the locations for speech production and motor control functions remain in the left hemisphere) (Elliot, Weeks, & Chua, 1994; Meegan, Maraj, Weeks & Chua, 2006; Weeks, Chua, Weinberg, Elliot & Cheyne, 2002). This reorganisation presents as a processing difficulty for this group particularly in light of the incomplete corpus callosum. Bunn, Roy and Elliot, (2007) suggest that the combination of these neurological differences means that the processing of information for speech production (and subsequent motor action) is impaired as information is lost or degraded.

2.2.2 Oral structure and anatomy

It is well established that people with DS present with orofacial structural differences that may have an impact on successful speech articulation. These include palatal shape and size, tongue size and dentition. The following section will present an overview of the literature related to these structural differences and will consider the impact these may have on speech articulation. Section 2.4.9 will provide further discussion in relation to sibilants.

2.2.2.1 Palatal size and shape

Early investigations of palate shape and size in people with DS identified structural differences compared with typical speakers (for both adults and children). Redman, Shapiro and Gorlin (1964) measured the width, length and height (which they labelled the *palatal index*) of normal children and adults, and Shapiro, Gorlin, Redman and Bruhl (1967) applied this palatal index to people (children and adults) with DS. Both studies revealed that subjects with DS differed to normal measurements in width (more narrow), and length (shorter) but noted that palatal height in males with DS fell within normal ranges. Further studies find supporting results. For example, Westerman, Johnson and Cohen (1974) compared palatal measures from 40 people with DS (16-29yrs) with 44 people without DS (7-24yrs). Their averaged measures agreed with results from Shapiro et al. (1967), also finding that the group with DS had significantly narrower, shorter and lower palates than the control group. The results remained stable when adjusted for age and gender. Similarly, Panchon-Ruiz, Jornet-Carrillo and Sanchez del Campo (2000) found differences in palate length, width and height between adults with DS and normal adults and noted that all measures for the normal group were significantly greater than those of the adults with DS (also noted in Dellavia et al., 2007).

Enhanced by imaging techniques, more recent studies have supported these earlier findings. Uong et al. (2001) created MRI scans of the upper airway in 11 children with DS and 14 age-matched typical controls and measured (among other things) palatal length (but provided no measures of palatal height). They found that, in line with previous studies, palatal length was significantly shorter in the group with DS than the TD controls. Vorperian, Kent and Gentry (2004) also found the same differences in hard palate length using MRI with 4 children with DS. Further studies in teenagers (9-17 years) with DS found only oral volume to be significantly different when compared with a typical control group (Xue, Kaine & Ng, 2010). However Xue et al. (2010) presented measures related to pharyngeal and vocal tract length, which are not often reported on. Their oral cavity measurement findings are in line with previous studies, but they did not note differences for the pharyngeal measures. The authors suggest that their different findings may be related to sampling error. However, their results may show that structural differences in people with DS are confined to the oral cavity. A more detailed look at the palatal structure found in speakers with DS was performed by Škrinjarić, Glavina and Jukić (2004) who analysed dental plaster casts and noted a high presence of the palate shape in children and young adults (3-20 years) with DS as being shelf-like (identified by a step-like transition of palatal prominences). Additionally, they noted a higher presence of this palate shape in younger speakers with DS, compared to adults with DS (with no presence of this palate shape in the control speakers). Their findings are interesting as they provide a detailed DS-specific shape which has not previously reported and also suggest that palate shape changes with age in people with DS (with the shelf-like shape decreasing).

Conversely, Bhagyalakshmi, Renukarya and Rajangam (2007) reported different palatal height measurements in their speakers with DS, compared to previous studies. They measured length, width and height using manual measures from dental impressions of 48 children with DS (6-16yrs) and 48 controls. Their findings concurred with the majority of research reported above: they found that the palate was significantly narrower and shorter in the group with DS. However, they also found that the palate was significantly higher in the group with DS compared to the controls. These different findings may be explained by the less reliable measurement techniques used in the Bhagyalakshmi et al. (2007) study (they used wax strips on plaster casts to establish their palatal measurements which may be less reliable than imaging techniques such as MRI).

Although there is some disagreement regarding palatal height, these studies provide clear evidence for the differences in palatal shape in people with DS (both adults and children). It has been suggested that these differences may affect lingual-palatal contact in speakers with DS (Bhagyalakshmi et al., 2007) as the normal sized tongue in relation to a smaller oral cavity may inhibit the coordination required for successful articulation (Xue et al., 2010). Although there is little concrete evidence to support this (see 2.4.10.1), claims are often made within studies of speech production in DS that palate shape differences may make precise articulations difficult as the normal sized tongue will be large in relation to the small and narrow palatal area (Dodd & Thompson, 2001; Smith & Stoel-Gammon, 1983, Stoel-Gammon, 1997, 2001, Uong et al., 2001).

2.2.2.2 Tongue size

Older accounts of the anatomical differences in people with DS indicated the presence of a larger than normal tongue (Cohen & Winer, 1965; Vogel, Mulliken & Kaban, 1986), termed as '*true macroglossia'.* As a result, these findings led to recommended surgical interventions to reduce the size of the tongue, with the aim to improve speech intelligibility. Considering more current research regarding tongue size, partial tongue reduction was surprisingly found to improve speech production in a few studies (Lemperle & Radu, 1980; Wexler, Peled, Rand, Mintzker & Feuerstein, 1986). However, neither of these studies provides objective measurements or details of actual speech changes. Conversely, Parsons, Iacono and Rozner (1987) assessed speech production ability in 18 children with DS who had undergone tongue reduction surgery and found that there were no significant post-therapy differences in the tongue surgery group compared to a non-surgery group. Margar-Bacal, Witzel and Munro (1987) also found no improvement in speech production after tongue reduction surgery. Although motivated by a misleading sense of *true macroglossia*, these findings potentially suggest that the tongue size in relation to the palate does not provide the main obstacle to successful speech articulation in children with DS.

In contrast to the earlier findings, recent studies agree that the tongue is the same size as age-matched controls (Uong et al., 2001) or even smaller (Guimaraes, Donnelly, Shott, Amin & Kalra, 2008) but appears large in relationship to the smaller than normal oral cavity (referred to as *relative macroglossia)* (Pilcher, 1998; Vorperian et al., 2004; Xue, Kaine & Ng, 2010). Guimaraes et al. (2008) measured the maximum anterior-to-posterior tongue diameter, midline sagittal area, and total tongue volume along with oral cavity measures (distance from mandible to vertebrae, mandible to the cranium and the width of the retroglossal airway). The measurements were all taken from MRI scans of 16 children with DS (mean age: 14.9 years). From the tongue and oral cavity measurements a ratio was calculated to determine the size of the tongue in comparison to the oral cavity. Their findings support the suggestion of relative macroglossia in DS as they found that the tongue was larger in comparison to craniofacial parameters than the control group. However, as this was a study of older, adolescent children, it is unknown whether these differences exist in a younger group of children with DS. Recent work on craniofacial development in mouse models with DS have noted that tongue size is normal during embryonic development, but the mandible is smaller (Billingsley et al., 2013).

The relative size and shape of the tongue in comparison to the smaller hard palate may result in problems with specific lingual articulations due to the precise tongue-palate contact required for consonants such as sibilants. However, it is well established that speakers are adept at creating different articulations to achieve certain acoustic targets (Perkell, Matthies, Svirsky & Jordan, 1993). Whilst this may be true it is possible to suggest that the combined difficulties experienced in DS may not allow this compensation to occur easily.

2.2.3 Dentition

The presence of dental malformations in people with DS is high. Cohen and Winer (1965) identify presence of dental disturbances in 73% of their 123 participants with DS. More recently, Meštrović, Mikšić, Štefanac-Papić and Stipetić (2002) identified malocclusions in 92% of 112 subjects with DS, suggesting that a very high proportion of children and adults with DS (their subjects ranged from 2-36 years) experience some form of abnormal dentition. These malformations usually manifest as malocclusions (Carlstedt, Henningsson & Dahllof, 2003; Oliveira, Paiva, Campos,

& Czeresnia, 2008; Oliveira, Prodeus, Torres, Marins & Paiva, 2010), such as Angle Class III (Ardran, Harker & Kemp, 1972; Backman, Grever-Sjolaner, Bengtsson, Persson & Johansson, 2007; Cohen & Winer, 1965) which can result in a low and flaccid tongue (Johnson & Sandy, 1999) and anterior open bite (López-Pérez, Borges-Yánez & Lopez-Morales, 2008; Suri, Tompson & Cornfoot, 2010). Suri et al. (2010) noted that the presence of an anterior open bite or open bite was seen frequently in their group of 25 young people with DS (52% had an overbite of less than 1mm and 48% had an anterior crossbite, compared to 1 speaker in the control group). They also noted that the tooth lengths in the DS group were significantly smaller (as found in Cohen & Winer, 1965). Abnormal dentition in this group is related to the contribution of muscle hypotonia, midface hypoplasia, mouth posture and structural defects (Borges, Oliveira, Paiva, Campos & Czeresnia, 2008; Pilcher, 1998). Though few studies have directly investigated the link, dentition differences (alongside many other factors) in DS have been suggested to have a negative impact on articulation (Rondal & Edwards, 1997; Pilcher, 1998).

However, establishing the link between dentition and speech production is complicated (see 2.4.10.2 for more discussion). Indeed, Moller (1994) reviewed a series of studies into dental effects on speech production and concluded that there "is no cause-and-effect relationship" (p.16) between malocclusions and speech production. While abnormal dentition may not ensure a speech production difficulty, it may be expected that speech sounds requiring the teeth as articulators (such as sibilant fricatives) would be affected.

2.2.4 Hearing loss

In addition to the neurological and structural differences mentioned above, people with DS are well known to experience levels of both conductive and sensorineural hearing difficulty from birth (Balkany, Downs, Jafek & Krajicek, 1979; Keiser, Montague, Wold, Maune & Pattison, 1981; Porter & Tharpe, 2010). Although presence of hearing loss is a recognised feature in children with DS, reported numbers can vary. Shott, Joseph and Heithaus (2001) identify conductive hearing loss in 96% of pre-school children and investigations of older children have noted similar levels (90%: McPherson, Lai, Leung, & Ng, 2007). Conductive hearing loss is the most common type of hearing loss experienced in DS, generally caused by

Otitis Media with effusion (OME) (also known as glue ear). The presence of OME can reduce the ability of the middle ear to transmit high frequency vibrations to the inner ear. It has been suggested that the anatomical differences in DS such as a smaller outer ear, narrow auditory canal, and malformed cochlea (Venail, Gardiner & Mondain, 2004) will contribute to the high levels of hearing loss in this group, with middle ear problems resulting in the high incidence of OME in this group.

The high incidence of hearing loss in DS has frequently been suggested to affect speech and language developing appropriately (Brown-Sweeney & Smith, 1997; Chapman et al, 1991; Roizen, 1997; Stoel-Gammon, 1997). However, Laws and Bishop (2004) note that the evidence for the effect of hearing loss on language development in DS is inconsistent, and suggest that as individuals with good hearing can have language impairment, the language deficit in DS is not a result of hearing difficulties (though it does contribute). Though more recently, Laws and Hall (2014) highlight that many studies of speech and language ability in DS exclude participants with hearing difficulties. In contrast, the authors included individuals with hearing loss and noted low levels of speech accuracy that they contributed to these hearing losses. The remaining literature provides little evidence of the impact of hearing loss on speech production in this population, but this may be a result of the complexity of these individuals and selecting hearing loss for sole analysis is not possible. It may be considered that hearing loss will have some impact on speech production particularly as differentiating between some speech sounds (particularly sibilants) has been found to rely on high frequency discrimination (Perkell et al., 2004). This will be further discussed in relation to data on typically developing children in section 2.4.8.3 which will consider the impact of hearing loss on successful sibilant production.

2.2.5 Muscular control and motor functioning

Alongside structural and anatomical differences it has also been reported that people with DS perform poorly in most areas of motor functioning (Frith & Frith, 1974; Spano et al., 1990; Spender et al., 1995) possibly as a result of muscle hypotonia. The following section will review the literature regarding the presence and impact of hypotonia and motor functioning difficulties in people with DS.

2.2.5.1 Muscle hypotonicity

People with DS frequently show presence of muscle hypotonia which affects all muscle groups (McIntire & Dutch (1964) found hypotonia in all major muscle groups in 97.7% of children under 6 years), many of which will have an effect on speech production, and may affect motor development (Lauteslager, Verneer & Helders, 1998). Muscle hypotonicity can affect speech production in many different ways, for example, hypotonicity of facial muscles (Cunningham, 1987), the tongue (Kumin & Bahr, 1999) and the lips (Mizuno & Ueda, 2001) may affect the ability to create precise speech articulations and may also effect supra-laryngeal voice quality, while hypotonicity of muscles at the larynx will affect laryngeal voice quality (Pryce 1994). Hypotonia has also been found to affect proprioceptive feedback (Dyer, Gunn, Rauh & Berry, 1990) which is an important part of normal speech development and important for speech production. However, in a review article on gross and fine motor development in DS, Sacks and Buckley (2003) state that hypotonia probably has little effect on motor development in DS. Although, they do note that speech motor skills are different to other motor skills so hypotonia may well play a part in the speech problems found in DS.

2.2.5.2 Oral motor function

As noted in section 2.2.5.1 above, it has been suggested that the motor control differences in DS are related to the presence of hypotonia (Lauteslager, Vermeer & Helders, 1998), and the reduced size of the cerebellum (Lana-Elola, Watson-Scales, Fisher & Tybulewicz, 2011). It is well reported that motor difficulties exist in this group (Sacks & Buckley, 2003) and have a negative impact on speech production. However, as Laws and Bishop (2004) note, there is sparse research available that confirms a relationship between motor skill and speech development for these speakers. The majority of studies into motor control have focused on finger tapping and tracking (Frith & Frith, 1974; Latash, Kang & Patterson, 2002); walking, reaching and grasping reactions, ball skills and balance (Carr, 1970; Haley, 1986; Jobling, 1998; Palisano et al., 2001; Spano et al., 1999) and oral motor functioning, such as swallowing and chewing (Kumin, 1994; Spender et al., 1995).

Oral motor functioning problems relate to difficulties controlling the oral musculature that may be involved in oral movements such as swallowing, chewing and speech. Spender and colleagues (1996) compared oral-motor functioning in 14 young children with DS (11-34 months) and a group of cognitively aged-matched TD children. They found that the children with DS had poor jaw function, intermittent lip closure and arrhythmic tongue movements (Spender et al., 1995, 1996) which may all contribute to speech difficulties. These studies provide some detailed information regarding motor abilities in this group, but otherwise information on oromotor skills is limited. More recently, Barnes, Roberts, Mirrett, Sideris and Misenheimer (2006) provided detailed information on oral-motor development in 34 boys with DS (4-16 years) using the Oral Speech Motor Protocol (Robbins & Klee, 1987), which included oral function tasks (imitation of oral movements) and speech function tasks (phoneme, syllable, word production/repetition and DDK). Their results found that children with DS performed significantly better at oral function tasks than speech function tasks, suggesting that early studies of oral-motor control may not be applicable to our understanding of speech motor functioning in children with DS. This study also identified an improvement in oral and speech function tasks with age. Using the same oral-motor task in 15 children with DS (8-19 years), Cleland et al. (2010) did not find a relationship with age. Though they did identify a significant relationship for the Robbins Klee Protocol and a percentage consonants correct measure for children, suggesting that motor ability is linked to phonological production abilities. The findings from the Barnes et al. (2006) study differ from Cleland et al. (2010) possibly due to selection criteria. The participants included in the Cleland et al. (2010) study were selected as they presented with speech sound difficulties. No such inclusion criteria were applied in Barnes et al. (2006).

Although a relationship was identified between oral-motor ability and speech production, as supported by findings in Barnes et al. (2006), deficits in oral-motor functioning may be difficult to link to the articulation of speech. It is increasingly acknowledged that the use of oro-motor assessments for information on speech motor ability is limited. In a review of the literature on oro-motor vs speech motor tasks, Weismer (2006) points out that some researchers find assessment of nonverbal motor skills (as assessed in the Robbins and Klee Protocol) inadequate for understanding the speech motor control process. If this view is accepted then it appears that specific studies on speech motor control in DS are currently lacking.

2.2.5.3 Speech motor function

Speech motor control has been defined as the combination of planning of movements involved in speech, and the execution of those movements via muscle and structural displacements (Kent, 2000).

Investigations of speech motor control in typical populations have identified variability in articulation (duration, amplitude, spectral measures) (Lee, Potamianous & Naryanan, 1999; Walsh & Smith, 2002), ability to perform oral Diadochokinesis (DDK) tasks (Thoonen, Maassen, Gabreels & Schreuder, 1994), speech timing and co-articulation ability (Zharkova, Hewlett & Hardcastle, 2011) as indications of speech motor abilities. These particular tasks have also been used for identifying levels of speech motor difficulties in children with speech sound disorders (Preston & Koenig, 2011).

There are relatively few studies that look specifically at speech motor control in DS. Most research on speech motor ability in this group tends to focus on measures of oral-motor control, such as the Robbins-Klee measure, and do not treat speech motor control and oral motor control differently (e.g. Kumin, 2006). Information on the impact of fine motor control difficulties on speech production is more appropriately gained from studies on speech motor ability in this group (similar to those mentioned above), rather than oro-motor functioning, particularly in light of findings from Barnes et al. (2006) who note that boys with DS exhibited more errors in speech function tasks (such as phoneme and syllable production) than oral function tasks (e.g. lip protrusion, mandible opening, tongue protrusion; all performed without voicing). Bunton et al. (2007) note that the suggestion that speech-motor systems in DS are impaired was first proposed in the late 1970s. For example, Dodd, (1976) who identified more inconsistent errors in children with DS compared to cognitively age-matched peers. Further evidence for speech motor difficulties derives from a body of work by Kumin (1999; 2006) which is based on parental surveys rather than quantitative speech measurements. Kumin's (2006) large parental survey identified speech motor difficulties with the following questions: *'My* *child had low tone in the muscles of the face (lips, tongue and cheeks) in infancy*' and '*My child currently has low tone in the muscles of the face (lips, tongue and cheeks*'. Her results found that 32.8% of the respondents answered 'always' to the first, and 13.7% answered 'never'. 15.6% answered 'always' to the second question and 23.4% answered 'never'. The following presentation and interpretation of these findings in Kumin's study provide weak support for speech motor difficulties in DS. In particular, the identification of 'low tone' as a representation of speech motor ability is misleading and more likely to identify levels of hypotonia in this group. Kumin (2006) concludes from this that the majority of respondents indicated that their child had some level of oral motor difficulty, although the highest count for both questions was for the answer '*sometimes*'.

Therefore evidence for speech motor difficulties as identified from actual speech production is limited. Of the studies that do exist concerning speech motor abilities in people with DS, the focus has been on timing, variability and DDK measures. The most detailed study to date is Brown-Sweeney and Smith (1997). This study employed acoustic techniques to analyse speech timing and speech precision in two groups of 8 children with DS (aged 6;8 –7;9 years and 11;10-12;10 years) and in a group of age-matched, TD children. The authors identified higher levels of temporal variability only in the closure phase of their target plosives (not in vowels, VOT or word durations) which they attribute to delays in speech motor development. Brown-Sweeney and Smith (1997) did not provide evidence of age-related variability (similar to findings in Cleland et al., 2010). By performing informal investigations, the authors suggest that the production variability observed in their participants predicts low articulation accuracy. This is a problematic conclusion as it was based on the presence of observed trends in some speakers. Furthermore, the data included in the variability measurements did not include any productions considered perceptually unacceptable.

Variability in speech production in DS has been identified increasingly with, for example, Dodd and Thompson (2001) suggesting that the variability found in children with DS is related to planning difficulties. The authors reject the influence of oral-motor difficulties on the inconsistencies noted in their speakers, due to the similar phonological abilities in their children with DS and a control group of children with inconsistent phonological disorder. Cleland et al. (2010) argue that this is a simplistic conclusion as oral-motor skills were not measured in this study. It can also be noted that the nature of the data analysis in Dodd and Thompson (2001) would not allow for variability measures that commonly identify speech motor difficulties. Stronger evidence of speech motor difficulties were identified in Timmins et al. (2007), who found high levels of within speaker articulation variability in the production of /s/ and /ʃ/ in 6 children with DS (aged 10-18 years). They concluded that this increased variability could result from an immature motor system, suggesting a delay in motor control rather than a delay in phonology but only provide a small set of speakers and data. Further evidence for speech motor deficits in this group has also been supported by studies showing prosodic and timing difficulties (Heselwood, Bray & Crookston, 1995; Shriberg & Widder, 1990). Additionally, evidence of vowel and consonant problems in adults with DS, led Bunton et al. (2011) to support the notion of speech motor difficulties in their speakers as the phonetic errors they identified related to tongue posture and control. Their perceptual findings indicated uncoordinated articulatory behaviour. Interestingly, the findings presented in Bunton et al. are not dissimilar to those identified in previous perceptual studies which do not argue for any motor difficulties per se, but the difference lies in the implementation of instrumental analysis providing phonetic detail.

The use of DDK tasks to assess speech motor control in DS has been employed by a few studies and results are conflicting. Some studies have suggested that individuals with DS show slower rates than typical comparisons (Hamilton, 1993). The slower rates are often accompanied by inaccuracies (Roisin, Swift, Bless & Vetter, 1988). Brown-Sweeney & Smith (1997) found that their 7-12 year old speakers with DS performed monosyllabic and bisyllabic DDK tasks with longer durations than their TD group. Rather than rate they calculated variability for /pt/ sequences (using a Coefficient of Variation measure) and found that their DS group were more variable than controls. In contrast, McCann and Wrench (2007) did not find rate differences between their group of children with DS (n=12) and a cognitively age-matched TD group for DDK tasks, though they did find higher levels of sequencing inaccuracies (as evidenced by auditory analysis). Considering the amount of inaccuracies, they concluded that this finding suggested that the speech disorder evident in DS may be Childhood Apraxia of Speech (CAS). Similarly, Rupela and Manjula (2010) focused on DDK in DS as a sign of presence of CAS. This study looked at rate, accuracy and number of attempts at task. For monosyllabic DDK tasks, they found no significant differences between rate measures for 30 children with DS and cognitively-age matched typical children. Differences occurred when investigating variability and accuracy, reflecting results noted by McCann and Wrench (2007). These larger studies do not reflect previous findings (Hamilton, 1993; Rosin et al. 1998) but this may be related to different methodologies and sample sizes.

Evidence shows that children with DS present with fine motor difficulties which include oro-motor and speech motor difficulties. The evidence for these difficulties is limited to auditory investigations, or instrumental analyses of small speaker groups, and in some cases parental reports. Although there is increasing evidence from acoustic investigations of speech production to support these findings (Brown-Sweeny & Smith, 1997), the review above shows that research in this area is surprisingly still lacking.

2.2.6 Summary: factors associated with speech difficulties in Down's syndrome

People with DS show a combination of neurological differences (particularly cerebellar activity), structural alterations (palate shape and tongue size), hearing loss and motor control deficits that have been suggested to contribute to the problems in speech production identified in this population. However establishing a link between these differences and speech ability is complex and little concrete evidence exists to date. For example, no studies exist that have measured speech and palate shape, from the same speakers with DS. Additionally, there are mixed conclusions about the impact of hearing loss on these speakers. Although there are established measures (e.g. speech variability and DDK) for the identification of speech motor control difficulties, there is a surprising lack of evidence for disordered speech motor control in DS using these particular measures.

2.3 Speech production in Down's syndrome

One of the defining features in young people with DS is their difficulty with speech articulation. Speech production abilities in DS have been widely reported in small case studies, group studies and review articles (e.g. Kent & Vorperian, 2013; Kumin, 1994; Roberts et al., 2007; Stoel-Gammon, 1997; Timmins et al., 2009) with articles appearing from the early 20th century to the present day. As reviewed above, speech errors can occur in relation to many factors identified in this group of speakers.

2.3.1 Speech production in adults with Down's syndrome

Data on speech behaviour in adults with DS is limited. Hamilton (1993) provides detailed articulation information from three young adults (aged 17, 17 and 20) which, although provides evidence to support Rondal and Comblain's (1996) claim that adults with DS perform at a similar level to children with DS in speech production ability, it is limited in sample size, and the young ages taken to represent adulthood. Bunton et al. (2007) provided phonetic error information for five adult males with DS (aged 26, 27, 29, 36, 39) and found heterogenic behaviours of speech intelligibility (41%-75%) and noted that speakers who scored similarly on their intelligibility measure did not use the same speech errors. They identified the most severely affected phonetic features as initial cluster reduction, vowel placement errors, and place of production for stops and fricatives. These error findings are similar (particularly initial cluster reduction) to studies on speech errors in children with DS (see 2.3.2.2 below). However, the authors found that there were no errors in the alveolar-palatal contrast (for /s/-/ʃ/ distinction) which they related to either the limited amount of target items, or that their findings indicated that individuals with DS continue to improve their speech production into adulthood. This is a strong claim made on the basis of only one production of each target sound and does not reflect the high levels of variability that would be expected in individuals with DS. Nonetheless, this study provides evidence for difficulties with speech motor control in adults with DS with errors previously unidentified in this age group. These findings suggest that adults with DS do not acquire typical speech patterns but perform at similar levels to children with DS.

2.3.2 Speech production in children with Down's syndrome

The pervading finding in speech research in this group is that children with DS present with speech difficulties that result in high levels of unintelligibility (Kumin, 1994; Rondal & Edwards, 1997). Intelligibility in speech can be affected by difficulties with any aspect of speech production, but is often related to high levels of variability (Newman, Clouse & Burnham, 2010), possibly as a result of speech motor difficulties. Speech production analysis to date has identified that people with DS show difficulties with consonant and vowel production, prosody (Heselwood, Bray & Crookston, 1995; Shriberg & Widder, 1990; Stojanovick, 2011), voice (Bolfan-Stosic & Hedever, 1999; Lee, Thorpe & Verhoeven, 2009; Moura, et al., 2008) and connected speech (Barnes, et al., 2009). Despite the variety of findings and continuous study, defining the speech pattern and difficulty of this group is still considered complicated. These complications have their roots in the many different causes that may have an impact on speech production (structural differences, hearing loss, & speech motor deficits). A further complication with the investigation of speech production in this group is the nature of the speech studies so far. As highlighted by Stoel-Gammon (1997), research itself varies regarding the way that typically developing children are compared with children with DS, with some matched for chronological age and others of cognitive age and in some cases, language age. Studies also compare speakers with DS to speakers with other genetic disorders (e.g. Fragile X Syndrome) or phonological impairments. As a result there is considerable variation in the reporting of speech production and development in DS displaying a delayed or deviant pattern. Another final point to consider is the reported heterogeneity of individuals with DS which can result in considerable variation of linguistic performance.

The following section will present a review of studies on speech abilities in children with DS. Traditionally, reviews of speech in DS begin with pre-linguistic vocal behaviour and then continue through studies investigating the further stages of speech development. This review will present a similar structure though will divide studies into those that use an auditory approach and those that also apply instrumental analysis.

2.3.2.1 Pre-linguistic development

Speech development is preceded by an important period of pre-linguistic development. Findings are inconsistent, with some studies (Dodd, 1972; Smith & Oller, 1981) suggesting that pre-linguistic development in infants with DS shows no sign of being either atypical or delayed. Dodd (1972) looked at the babbling stages of 10 infants aged 9-13 months (investigating the phonetic nature of utterances, e.g. vowels and consonants produced) and found no statistical differences when comparisons were made with 10 typically developing infants matched for chronological age. Smith and Oller (1981) also reported on phonetic characteristics of babbling and further analysed age of babbling onset. They concluded that there were “substantial similarities” (p.46) in the production of reduplicated babbling (repetition of syllables) in their DS and typical infant groups (up to 15 months). Similarly, longitudinal research by Steffens, Oller, Lynch and Urbano, (1992) reported similarities with the findings from some of the previous studies, with the 13 infants with DS (aged 4 to 18 months) they studied having development patterns more similar to their 27 typically developing, aged matched control infants. However, they acknowledged that the spacing between their recording intervals may have been too long and that larger data samples should have been recorded in order to allow a more detailed analysis of development in the two groups of infants. In a similar study to Smith and Oller (1981), Smith and Stoel-Gammon (1996) focused on the development and use of particular types of pre-linguistic babbling, reduplicated (e.g. ‘bababa’) versus variegated (e.g. ‘bada’) babbling, studying 9 infants with DS from 6 months to 2 years of age. They compared their results with findings from previous studies of age-matched typically developing infants and found patterns of particular babbling usage to be similar across the two groups (approximately 8 months). Smith and Stoel-Gammon also looked at the phonetic complexity of vocalisations but noted no increase in complexity with age in the infants with DS which they found to be similar to the normally developing infants in Smith, Brown-Sweeney and Stoel-Gammon (1989).

Both of these studies reported that there was no delay in the emergence of babbling for the infants with DS and also no apparent differences in segmental types produced. However, Lynch, et al. (1995), analysing the same data as Steffens et al.

(1992), analysed the age of babbling onset in 13 infants with DS (0;4 to 1;6 yrs) and 27 age-matched typically developing infants, and found a significant difference in the age of babbling onset, with the infants with DS not showing signs of babbling until 9 months whereas the mean onset of babbling in the typically developing infants was around 6 months. The early onset ages of the TD group in this study (compared to others above) would result in a difference of onset age, but the findings from Lynch et al. (1995) show a similar age of onset to typical comparisons in previous studies (Smith & Oller, 1981; Smith & Stoel-Gammon, 1989). This suggests that the typical age of babbling onset is variable, and that perhaps the variability identified across these studies for children with DS is within normal ranges. Despite some contradictory findings, at the onset of linguistic development most studies find that there are no differences in emergence of phonemes or types of segments produced at this stage.

2.3.2.2 Phonological investigations of speech in children with Down's syndrome

The transition from babbling to real word production is well documented in typical speech development. Children begin producing protowords, CV structures that are meaningful linguistically, around 9 months of age with the phonemes of English beginning to be established within basic word structures from this point onwards. Findings from Smith's (1977, 1984, cited in Stoel-Gammon, 2001) longitudinal research found that children with DS start to demonstrate a differing speech pattern at the emergence of meaningful consonant and vowel production (14 months for TD children, 21 months for children with DS).

Sokol and Fey (2013) provided additional evidence for delays from a similar age group as studied by Smith. Their participants included 26 children with DS at 22 to 34 months, compared to an aged-matched group of children with developmental delays but no DS (NDS). Smith's work was interested in the onset of meaningful speech, however Sokol and Fey investigated utterances containing CV or VC sequences. They calculated the number of English consonants produced at least twice in the child's speech sample. Their findings at 22 months indicated no differences between the two groups. However, recordings made 18 months later of the same children found that the NDS group produced a greater number and variety of consonant types than the children with DS. The authors conclude that this later difference is a clear indication that speech development difficulties in children with DS cannot be attributed to a general developmental delay. Importantly they also noted non-native (to English) errors such as palatal stops and velar fricatives. These tokens were understandably not included in their calculations for phonological system but the frequent focus of identifying phonemic inventories in children with DS (as will be discussed below) runs the risk of ignoring important articulation errors (as noted in the study by Sokol and Fey).

Longitudinal research is limited in this population with many studies comparing speech ability in children with DS with TD controls or standardised norms. However, one longitudinal study, Smith and Stoel-Gammon (1983), found parallels with typical developmental processes when comparing the development of plosive production in 5 children with DS (followed from 3 to 6 years), and 4 typical developing children (followed from birth to 3 years). Smith and Stoel-Gammon also looked at four developmentally important phonological processes. They found that final stop deletion and initial stop de-aspiration in the TD children stopped by around 3 years of age, but initial cluster reduction and final stop devoicing were less adult-like in both the TD children and those with DS. They noted that further development in their groups showed large differences, resulting in a four year difference in achieving similar levels of proficiency. On the basis of these findings, the authors concluded that phonological acquisition is delayed for children with DS. The authors pointed out that their sample was small, both in respect to the linguistic variables examined and the number of children studied. Particularly, the narrow focus on typical phonological processes limits the further investigation of the presence of atypical errors. Kumin et al. (2000) presented a larger longitudinal study of children from 9 months to 9 years and identified patterns of consonant acquisition dissimilar to those expected in typical development. Considering the small sample presented by Smith and Stoel-Gammon (1983), the atypical patterns identified by Kumin et al. (2000), and the acknowledged levels of between-speaker variability in DS, it is surprising that no other longitudinal studies of speech production in DS exist. The findings from Smith and Stoel-Gammon (1983) are regularly supported by cross-sectional studies rather than longitudinal studies. Furthermore, the majority of these studies perform systematic phonological analyses on the speech data, which by nature ignore phonetic errors to focus on observations of normal phonological acquisition (Miccio & Scarpino, 2008). Possibly as a result of analysis decisions, these studies conclude that children with DS present with phonological processes typical to children with DS (e.g. cluster reduction, final consonant deletion, stopping of fricatives and affricates and gliding, (Stoel-Gammon, 2001)) but at a later stage. Overall, the many studies of speech production in children with DS (see Table 2-1) can be divided into those who support a pattern of developmental delay, and those who agree to some degree with this finding, but also provide evidence of atypical speech behaviours. The majority of these former studies are old and present data from small groups of young children (Bleile & Schwarz, 1984; Bodine, 1974; Crosley & Dowling, 1989; Crosley & Dowling, 1991; Mackay & Hodson, 1982; Stoel-Gammon, 1980; van Borsel, 1996).

However, studies that do present atypical speech patterns often dismiss these particular findings (Cleland et al., 2010; Dodd, 1976; Iacono, 1998; Roberts et al., 2005; Rupela & Manjula, 2007; Sommers, Patterson & Wildgen, 1988ab) and provide very little detail about such errors. Some studies have described atypical errors e.g. backing of /s/ and affrication of /ʃ/ (Dodd, 1976), and inconsistency of substitutions (Dodd, 1976; Dodd & Thompson, 2001; So & Dodd, 1994) but often errors are described in terms of processes. For example, Roberts et al. (2005) identified mostly typical errors in boys with DS, but also a high number of atypical phonological processes were also found, including lateralization of sibilants, de-affrication and deletion of nasals. Similarly, Cleland et al. (2010) identified typical phonological processes in a group of young people with DS but also noted presence of atypical processes in the speech of all 15 participants. Rupela & Manjula (2007) also found evidence of developmental errors in speakers with DS, but also evidence of atypical errors, for example, /m/ substituted by [j], /g/ by [v], /j/ by [n]. Additionally, they noted 38 different phonological processes in their DS group, with only 16 of these noted in the TD group. This pattern of developmental and atypical errors is common throughout speech studies in DS (Sommers et al. 1988ab) but surprisingly there are very little studies that provide detail of the phonetic nature of these atypical errors.

Authors, year	DS (n)	DS (age)	Control (n, age)	Delayed Y/N	Evidence of atypical errors Y/N
Dodd (1976)	10	6-15 yrs			Y
Stoel-Gammon (1980)	4	3;10, 5;6, 6;1 6;3		Y	
Mackay & Hodson (1982)	20	6-15yrs		Y	
Smith & Stoel-Gammon (1983)	5	3 - 6yrs	TD 4 , 18-26mths	Y	
Bleile and Schwarz (1984)	3	3;4, 3;6, 4;6		Y	
van Borsel (1988)	5	16-20 yrs		Y	Y
Rosin, Swift, Bless, & Vetter (1988)	10	10-18 yrs	TD 20, 5-19 yrs NDS 10, 12-19 yrs		Y
Sommers, Patterson and Wildgen (1988)	24	13-17yrs 15-22 yrs		Y	Y
Sommers, Reinhart and Sistrunk (1988)	24	13-17yrs 15-22 yrs		Y	Y
Van Borsel (1988)	5	16-20 yrs			Y
Crosley & Dowling (1989)	22	6-13 yrs			Y
Crosley & Dowling (1991)	22	6-13 yrs			Y
So & Dodd (1994)	14	4-9 yrs	TD , NDS 4-9yrs	Y	Y
Kumin, Councill & Goodman (1994)	60	0;9-9;0			Y
Van Borsel (1996)	20	15-24 yrs	TD 2-4 yrs	Y	Y
Iacono (1998)	5	5-7 yrs		Y	
Dodd & Thompson (2001)	15	5-16 yrs	TD 10, 2-5 yrs, IPD 10, 7-10 yrs		Y
Roberts et al (2005)	32	4-13 yrs	TD 33, FXS 50	Y	Y
Rupela, Manjula & Velleman (2010)	30	11-15yrs	TD 6, 4-5 yrs; NDS 7, 11-15yrs	Y	Y
van Bysterveldt (2009)	77	5-15yrs		Y	Y
Cleland et al (2010)	15	9-18 yrs	4-7 yrs	Y	Y
Sokol and Fey (2013)	26	2;2-3;4	NDS 22, 2;2-3;4	Y	Y

Table 2-1: Phonological studies of consonant production in people with Down syndrome (DS). Table presents authors and year of publication, number of participants with DS, age of participants with DS, number of control subjects and age, whether study concludes with a delayed phonological finding and/or atypical errors. TD: typically developing, NDS: participants with cognitive delay that is not DS, FXS: Fragile X Syndrome, IPD: inconsistent phonological disorder

It is argued that the auditory, phonological nature of these investigations leads researchers to ignore atypical phonetic errors identified in these studies (e.g. as noted in Sokol & Fey, 2013; Sommers et al. 1988a), and that more atypical errors could only be identified by instrumental analyses. However, the studies that found atypical errors alongside developmental errors, all employed auditory analysis, but also presented more detail about the errors than others in Table 2-1 which suggests that researcher decisions and level of transcription may also have an impact on what type of errors are identified. For example, detailed auditory phonetic analysis in Heselwood (1997) identified click sounds for target approximants, stops and fricatives in the speech of an adult male with DS. The presence of these errors suggests that phonetic investigation of speech in DS is necessary to fully understand the articulatory difficulties in this group.

In summary, the studies above provide evidence of consonant production difficulties in children with DS. The persisting finding shows that children with DS present with a delayed phonological profile. However, studies tend to focus on the phonology of speech production (applying phonological process analysis) and are auditory based. The general conclusion of a speech delay is problematic as many of the studies above also report atypical productions. These atypical productions are often dismissed without further description or discussion. A possible explanation for this is that the methodology for analysis does not support the investigation of fine phonetic differences. While auditory analysis is valuable, it may also “be highly unreliable” (Wood, 2010:98). It is proposed that instrumental analysis is required in order to investigate the nature of these atypical productions in an objective manner.

2.3.2.3 Instrumental investigations of speech in Down’s syndrome

There are various instrumental techniques available in speech analysis (acoustic and articulatory) but they have been employed in only a few small studies to establish the speech characteristics of DS. Considering the large amount of perceptual consonant studies, there is a corresponding lack of studies presenting acoustic analyses on consonant production in people with DS. The information is often limited to case studies but even within these small groups, detailed articulatory information can be gained.

Callahan-Mandaluk, Zajac, Harris, Roberts and Cox (2006) used acoustic analysis to investigate duration and spectral qualities of fricative sounds produced by children with DS (aged 6;3-15;11), age-matched TD children and children with Fragile X syndrome. They found that the distinctions in duration between /s/ and /z/ patterned differently for children with DS, for example, /z/ was longer in duration than /s/, but this pattern was reversed for the typical children and the group with Fragile X syndrome. The acoustic analysis of /s/ and /ʃ/ noted more similar frequencies (indicating less distinction between places of articulation) for the children with DS and the children with Fragile X syndrome, compared to the productions of the TD children. This study provided fine phonetic information about DS indicating that the nature of the speech difficulty was different to TD speakers, and children with another intellectual disorder, in one respect (duration) but not others. And although a small study, the findings indicate that detailed analysis of the speech problems in DS is worthwhile and is necessary to understand articulatory differences in this population.

Instrumental techniques have also been used to investigate vowel behaviour in DS. These studies have noted vowel errors and duration differences in vowel production in DS (Brown & Sweeney, 1997; Bunton, Leddy & Miller, 2007; Bunton & Leddy, 2011; Moran, 1986; Moura et al., 2008; Pentz, 1987; Van Borsel, 1996; Whitworth & Bray, 2015) in comparison to typical speakers. These findings are not consistent across studies, however, as some studies of vowel production have found no differences in vowel duration and formant values in children and adults with DS compared to typical groups (Brown-Sweeney & Smith, 1997; Moran, 1986). Differences may be attributed to data elicitation, for example, Moran (1986) measured prolonged single vowel productions in comparison to monosyllabic words in Bunton and Leddy (2011). Bunton and Leddy (2011) presented vowel measures from two adults with DS and found that the vowel space was more centralized, vowel durations were longer and the articulatory space was smaller than two aged-matched controls. They reject the idea that these differences are caused by anatomical differences alone and suggest that the ability to control movements (within the constraints of an abnormal anatomical and physiological setting) affects the speech problems found in DS.

In the small group of studies concerning phonation in DS, instrumental analysis of fundamental frequency (F0) has also found conflicting results. Studies suggest that F0 is produced with both high and low F0 values (Lee, Thorpe & Verhoeven, 2009; Moran & Gilbert, 1982; Seifpanahi, Bakhtiar & Salmalian, 2011). For example, Pentz (1987) noted lower F0 values in 14 children with DS when compared with a typical group, whereas Lee et al. (2009) found high F0 values in children with DS.

Articulatory (EPG) studies of speech production in DS have identified evidence of atypical speech errors previously unidentified. Hamilton (1994) found asymmetrical articulation patterns in /s/ and /ʃ/ in 2 of her 3 subjects, and increased lingual palatal contact for target consonants. Similarly, Timmins et al. (2007) looked at /s/ and /ʃ/ production in a group of 6 children with DS and identified higher levels of variability for /ʃ/ than /s/, and noted atypical substitutions such as ingressive lateral fricatives, velar fricatives and palatal fricatives. Timmins et al. (2009) focussed solely on the production of /ʃ/ in a group of 20 children with DS and performed a descriptive analysis of articulation ability from assessment of EPG spatial data. They found that speakers with DS displayed disordered patterns of articulation for perceptually acceptable productions of /ʃ/ not found in the cognitively age-matched TD group, suggesting that the speech errors in DS are not similar to that of TD children. Although only analysing one particular speech sound, these findings provide evidence that the speech difficulties in DS are more complex than previous studies may have suggested.

Evidence from the instrumental studies above suggest that the speech problems experienced in DS are not a case of a simple phonological delay but indicate that there are phonetic difficulties (vowel distortions, duration differences) which are complicated and require closer analysis. The analyses techniques above may help to provide the articulatory information that could answer whether speech ability in DS is related to anatomy, motor control and/or muscular hypotonicity. However, whilst providing more insight into articulation errors, these studies are few and limited to small groups.

2.3.3 Summary: Speech production in Down's syndrome

The main findings from the studies on speech production in DS suggest that there is evidence for both a delay and a deviant pattern of phonological development. While the majority of smaller, older, studies assume a straightforward delay, many others note the additional presence of atypical features. Additionally, studies of speech in adults with DS note that articulation difficulties remain beyond childhood. In regard to these atypical features present in both children and adults with DS, there is general agreement that children with DS present with a greater number of speech errors (Parsons & Iacono, 1992), and a higher than normal level of inconsistency (Dodd, 1976; Stoel-Gammon, 1997) which may be related to speech motor difficulties (Kumin et al., 1994). However, consensus for the presence of atypical error types is lacking as these are only noted in small numbers and often not in the majority of speakers in studies. This could be a consequence of studies being centered around phonological processes based on auditory analysis. Auditory analyses, particularly as used in phonological studies, force the listener to categorise articulation movements into adult-like segments. Recently, Li, Munson, Edwards, Yoneyama and Hall (2011) highlighted the limits of phonological transcription of speech development in typical children by noting perceptually unidentified stages of articulation development. They argue that phonological transcription is inappropriate for the analysis of children's speech behaviour as it assumes children articulate sounds in the same way as adults (which their study found is not the case). This would doubly apply to children with DS who may also show articulations different to typical children (as well as adults). It is therefore suggested that error pattern types in DS speech may be better investigated using instrumental analyses. In the small amount of instrumental studies that exist, evidence has been provided of the potential impact of motor difficulties, combined with structural differences (linked to vowel production difficulties, articulation variability, F0 differences) and the presence of hypotonia (F0 differences and increased lingual-palatal contact). This study proposes to extend these investigations to consonant productions that are often in error in children with DS. As shown above (2.3.2.2) sibilant fricatives are often identified as problematic in children with DS. Furthermore these consonants are highly suitable for instrumental analysis.

2.4 Sibilant production in typically developing children, adults and people with Down's syndrome

2.4.1 Introduction

Sibilants are considered to be problematic for children with DS (Bunton et al., 2007; Roberts et al., 2005; Wood et al., 2009) particularly as they require a complicated articulation dependant on precise motor control of the tongue, and are acquired later in typical speech development. The sibilant fricatives are of particular interest as they require the presence of a stable narrowed tongue groove and are considered to be highly stable articulations. The supposed stability of these speech sounds make them ideal segments for investigations of articulatory variability related to speech motor difficulties. Additionally, these sounds also rely on a complex tongue constriction in relation to the palate and are acoustically dependent on the teeth (see section 2.4 below for a further discussion on these points). Furthermore there is evidence to suggest that discrimination between sibilant fricatives has been noted to be problematic in speakers with a hearing loss (Perkell et al., 2000). The nature of sibilant fricatives and the impact these features of DS have on successful production will be discussed in the following section. In this study, it is proposed that speech motor deficits can be investigated by the instrumental analysis of sibilant productions, providing fine phonetic detail on spatial variability and the nature of articulatory errors in people with DS.

2.4.2 Sibilant production in typical speech

Sibilants are consonant sounds that involve a manner of articulation where a narrow constriction of the articulators is created resulting in the presence of audible turbulent airflow. Laver (1999) noted that the criteria for classifying fricatives (including sibilants) have to include acoustic and aerodynamic factors as well as the articulatory considerations. These factors make sibilants complicated strictures to assess, requiring a collaboration of many different articulatory structures. As well as a narrow constriction in the oral cavity, glottal adjustments are also made to increase the amplitude of the oral friction. For example, in voiceless sibilant production, the glottal opening is widened to be greater than the oral constriction (Stevens, 1998). The combination of these factors suggests that the articulation of sibilants requires precise coordination between both oral and glottal configurations. This can be demonstrated by the significant acoustic difference a small articulation difference can make during the production of sibilants (Ladefoged & Maddieson, 1986). Ladefoged and Maddieson note that the articulators need to be held together very precisely in order to create the right channel for airflow and held for a noticeable period of time. This accuracy of articulation and duration results in the sibilant having a "greater constancy of shape in varying phonetic contexts in comparison with the corresponding stops" (Ladefoged & Maddison, 1986:57), a finding which has been consistently supported through the literature on sibilant production (Perkell et al., 2004). Ladefoged and Maddison (1986) describe sibilants as being a product of high-velocity airflow at the narrow constriction and then further obstruction by another constriction e.g. Shadle et al. (2006) found that the turbulent noise associated with /s/ is enhanced by the lower teeth being raised into position. The English language has two voiceless sibilants, /s/ and /ʃ/ both of which are produced with a narrowed grooved tongue constriction (channelling the airflow down the middle of the tongue) placed at the alveolar ridge for /s/ and the post-alveolar area of the palate for /ʃ/. Fricative sounds vary in articulatory complexity but the sibilants are considered to require a more precise articulation (Hardcastle, 1976; Shadle, 1985) than the non-sibilant fricatives /f, v/ and /θ, ð/.

The literature on sibilant articulation is large. This section will review the literature targeting mainly those topics relevant to the interplay of acoustic and articulatory features in the voiceless sibilant fricatives /s/ and /ʃ/.

2.4.3 Acoustic features of sibilant production

Sibilants are identified acoustically by constant aperiodic noise. In English there are two places of articulation used to produce the sibilant fricatives. These places of articulation can be represented acoustically by the frequency of the spectral peak of the frication portion. The literature is united in the acoustic differences between the production of the alveolar and post-alveolar sibilant. In adult male speakers the alveolar sibilant /s/ shows spectral peaks between 3.5 and 5 kHz and the post-alveolar sibilant /ʃ/ shows spectral peaks between 2.5 and 3.5kHz (the lower frequency related to the longer front cavity and lip rounding (Abbs & Minife, 1969; Behrens & Blumstein, 1988; Heinz & Stevens, 1961; Hughes & Halle, 1956; Jongman, Wayland & Wong, 2000; Shadle & Mair, 1996; Stevens, 1998). However, Jongman et al. (2000) note that the range of acoustic features that distinguish place of articulation for English sibilants is much wider than spectral peaks alone. They found that spectral peak location, spectral moments, normalised root mean square amplitude and relative amplitude all contribute to the place of articulation perception. However, unlike the non-sibilants, the sibilant fricatives carry perceptual cues in the friction portion (rather than in the fricative-vowel transition) (Harris, 1958). This has an impact on analysis, where studies can identify perceptually relevant information from the fricative without necessarily measuring transitional periods.

While studies agree that /s/ and /ʃ/ differ spectrally, this difference is less evident when looking at data from children (Nittrouer et al., 1989). Nittrouer et al. (1989) found that /s/ and /ʃ/ productions were less distinct in 3 year old participants than adult speakers, but also found that the spectral distinction increased with age. These findings were replicated by Nissen and Fox (2005).

2.4.4 Temporal features of sibilant production

Although Behrens and Blumstein (1988) in their study of adult males found no significant differences in duration of the friction noise for /s/ and /ʃ/, Nissen and Fox (1995) found that place of articulation was significantly related to fricative duration. They studied children and adult speakers producing voiceless sibilants in word-initial position and found that /s/ measured at 205ms and /ʃ/ at 199ms (these results were for both adults and children though they did note that the findings were shorter for the children). It seems that duration may be important in the production differences of /s/ and /ʃ/, particularly as Jongman (1989) found duration to be an important factor in the perception of place of articulation (30ms is required in order to identify /ʃ/ but 50ms is required to identify /s/). Greenberg, Carvey, Hitchcock and Chang (2003)’s more recent study of /s/ durations within connected speech, recorded durations of 125ms for /s/ in word initial position (much shorter than Nissen and Fox’s findings), which may be due to rate differences in connected speech tasks. From the two studies reported here it is unclear whether there is an established average range of duration for /s/ and /ʃ/ production or whether context and speaker are a factor. It is to be considered that our perception of the /s/~/ʃ/ distinction does not just rest on place of articulation but also on duration differences.

2.4.5 Articulatory features of sibilant production

2.4.5.1 Typical English /s/ production

The most common production for English /s/ is produced by either the tip of the tongue or the blade (with the tip behind the lower teeth) and all speakers of English are said to produce /s/ with the lower and upper teeth together (Ladefoged & Maddieson, 1996). Speakers can produce /s/ with either the tongue tip raised or lowered (Ogden, 2009). Narayanan et al. (1995) found that in /s/ production the tongue groove shape is determined by the apical or laminal nature of the tongue, with an apical production producing a deeper groove and more lateral contact when compared to a laminal production. As has been noted in instrumental studies (see section 2.5.3.1 below) the tongue groove shape is narrower than in the articulation of /ʃ/ (Ladefoged & Maddieson, 1996). Some early studies found that the groove ranged from 17mm to 6mm deep, though these were based on X-ray tracings. Stone (1991) presented data from ultrasound analysis that identified a groove depth of 6-8mm. More recent investigations have noted that English /s/ is produced with a groove depth between 3-12mm (Narayanan et al., 1995). Macafee (1983) describes the articulation of Glaswegian /s/ as retracted (also noted in Stuart-Smith, Timmins & Wrench, 2003) with the tongue tip raised. Stuart-Smith et al. (2003) point out that tongue tip raised /s/ opens up the lower cavity (which then becomes similar to the sub-lingual cavity created in /ʃ/ articulation), suggesting that speakers with tongue tip raised /s/ may present with acoustic productions of /s/ that sound similar to productions of /ʃ/. Similar retraction of /s/ articulation in English has been noted in /str/ clusters (Baker, Archangeli & Mielke, 2011), and has the same perceptual effect as noted by Stuart-Smith et al. (2003).

Along with tongue position, jaw position has been considered another important feature in the articulation of /s/ (Brunner, Fuchs & Perrier, 2009; Munson, 2004). The mandible has a high position during the production of /s/ (and /ʃ/), which is not explicitly related to the height of the tongue (Mooshammer, Hoole & Geumann, 2007). The groove configuration is created by the tip-blade region of the tongue and involves the coordination of many muscular systems. As well as maintaining the groove constriction, the tongue is held forward in the mouth (Hardcastle, 1976). Along with the palatal groove, dentition also adds to the acoustic effect of these articulations, with friction being produced against the back of the teeth (Narayanan, Alwan & Haker, 1995; Shadle, 1990).

A typical English /s/ production is dependent on a narrow lingual groove directing airflow down the midline of the oral cavity. The lower jaw is high, keeping the bottom and upper teeth together. The central oral airflow then collides with the back of the teeth before exiting the oral cavity. The successful production of /s/ relies on a complicated combination of oral structural settings, not just lingual. However, the lingual articulation is by far the most identifiable aspect of articulation for these speech sounds.

2.4.5.2 Typical English /ʃ/ production

English /ʃ/ tends to be complex, with research suggesting that the articulation involves the addition of lip rounding and the presence of a sub-lingual cavity (Stevens, 1998; Perkell et al., 2004). Both lip rounding and the sub-lingual cavity contribute to the low frequency energy attributed to /ʃ/ (as noted in 2.4.3 above). However, Shadle et al. (2009) suggest that the sub-lingual cavity is not crucial to the auditory distinction of /ʃ/ in comparison to /s/ but is one of many variables at hand to distinguish the two sibilants. Ladefoged and Maddison (1996) note that there are various descriptions regarding the place of articulation for /ʃ/ (palato-alveolar/alveolo-palatal/palatal) but they conclude that /ʃ/ is a "post-alveolar domed sibilant" (p.149). Like /s/, speakers produce /ʃ/ with the upper and lower teeth together and either have the tip of the tongue raised or lowered behind the lower teeth (Ladefoged & Maddison, 1996; Narayanan et al., 1995) and the central airstream from the groove articulation is obstructed by the lower teeth resulting in further friction (Stevens, 1998). The groove for /ʃ/ has been described as being wider and longer than the groove created in the production of English /s/ (Fletcher & Newman, 1991; Perkell et al., 2004) A further difference in the articulation of /s/ and /ʃ/ is that the part of the tongue immediately behind the /ʃ/ constriction is domed

(Ladefoged & Maddieson, 1996; Bresch, Riggs, Goldstein, Byrd, Lee & Narayanan, 2008) whereas this is hollowed for /s/.

The main articulatory differences between /s/ and /ʃ/ production are: the placement of the constriction (either alveolar or post-alveolar) (McLeod & Singh, 2009); the width of the narrow groove (Fletcher & Newman, 1991; Stone & Lundberg, 1996); the tongue is raised immediately behind the constriction for /ʃ/ but lowered for /s/ (Narayanan et al., 1995; Ladefoged & Maddieson, 1996) and /ʃ/ has additional lip rounding (Stevens, 1998; Ladefoged & Maddieson, 1996). McLeod and Singh (2009) provide detailed EPG information on the articulation of /s/ and /ʃ/. This is a critical review, which will be returned to in section 2.5.3, where EPG literature will be addressed in more detail.

2.4.6 Variability of sibilant production

As suggested in 2.4.1 above, sibilant fricatives are considered to be stable articulations. However, variability of sibilant articulation can occur in relation to typically development or contextual affects. The following sections will discuss the variability of sibilant production in both typically developing children and adults.

2.4.6.1 Variability in speech development

In typical speech development, it has been widely suggested that variability (relating to timing, amplitude and spectral measures) is related to development of speech motor control. This relationship tends to be supported with the findings that children present with higher levels of token-to-token speech variability than adults and become less variable as they get older (Cheng, Murdoch, Goozee & Scott, 2007; Cheng, Murdoch & Goozee, 2007; Goffman & Smith, 1999; Green, Moore, & Reilly, 2002; Kenney & Prather, 1986; Kent, 1976; Nittrouer, Estee, Lowenstein & Smith, 2005; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Zharkova, Hewlett & Hardcastle, 2011, 2012), and there is evidence from both segmental and direct kinematic studies to support this (Goffman & Smith 1999, Walsh & Smith, 2002).

The interpretations of these findings have led to a variety of explanations. A common suggestion is that higher levels of speech variability in children is a result of immature physiology, and that decreasing variability is related to neurological changes in the cortex and cerebellum (Koenig, Lucero & Perlman, 2008). Studies of speakers with speech disorders have interpreted high articulatory variability as an indication of reduced coordinative ability (Goffman, 2010). Additionally, some studies have suggested the variability is a positive sign of development, with high levels closely linked to periods of learning, particularly of new motor sequencing tasks (Goffman, Ertmer, & Erdle, 2002; Thelen & Smith, 1994).

Studies specific to temporal and spatial variability of sibilant production are supportive of these findings, regarding maturation of speech motor control reflected in articulation variability. Evidence for spatial and temporal variability in fricative production has been widely noted in studies of typical children (Munson, 2001; 2004) in relation to age. In their spatial and temporal variability study of fricative production, Koenig et al. (2008) identified higher levels of variability for /s/ and /z/ productions in children (5 and 10 year olds) compared to adults, but also noted that, in relation to spatial variability, temporal variability matures over a longer period of time (supporting findings from Smith and Goffman (1998)). Similarly, Lee et al. (1999) studied duration and temporal variability of word-initial /s/ production in a large number of children (n=436) and adults (n=56) and noted significantly higher levels of temporal within- and between-speaker variability at age 5 compared to age 18, which showed evidence of stabilisation at age 13. Further analysis of the same dataset (Gerosa, Lee, Giuliani & Narayanan, 2006) identified a reduction in within-speaker variability with age for a wider set of consonants (including WI /ʃ/). These findings are further supported and expanded by Zharkova et al. (2011, 2012) who found that typically developing children aged 6 to 9 years old show greater within-speaker variability in tongue position (as evidenced from Ultrasound analysis) than adults in the production of /s/ and /ʃ/. These studies also provide evidence for context-based differences in spatial variability in sibilant production. The tongue contour variability noted by Zharkova et al. (2011, 2012) was greater for /s/ in the context of /i/. The authors suggest that this variability may be related to the change in the mid-line profile of the tongue from fricative to vowel (which they state is greater than in a /su/ or /sa/ context). Munson (2001) also notes context-based variability, with spectral measurements of /s/ and /ʃ/ more variable in a /p/ context compared to /t/ context. Other studies however (e.g. Koenig et al. 2008; Lee et al. 1999), do not provide a variety of contexts to compare with these findings. In summary, typical children's sibilant production shows evidence of spatial and temporal variability in comparison to adult speakers, but importantly also variability related to context.

The above findings suggest that sibilant articulation is more variable in children than adults, but also that specific contexts affect these levels of variability. Furthermore, it is clear that typically, children do not achieve adult-like stability in timing and articulation of sibilants at the same time as perceptual phoneme acquisition.

2.4.6.2 Variability in adults

Once speakers present with an adult level of articulatory maturation, there is still some evidence of variability though considered low in comparison to other consonant segments. The low variability identified in sibilant fricative production is considered to be a result of the greater amount of articulatory control required for these articulations due to the complicated systems of muscle and motor requirements (Lavoie, 2001) and the perceptual impact minor articulatory changes can have on sibilant production (Lindblad & Lundqvist, 1994). Supporting this are findings from an EPG study of typical adult consonant production (Dromey & Saunders, 2009) which identified lower levels of within-speaker spatial variability in production of /s/ and /z/ compared to alveolar and velar stops. Newman, Clouse and Burnham (2001) measured typical acoustic variability of /s/ and /ʃ/ in adults (using spectral moments) in a range of vowel contexts (CV syllables) in order to assess levels of variability in their speakers and the impact of that variability on perception of these sounds. They found that speakers were variable (based on the standard deviations of acoustic measurements) and higher levels of variability impacted on listeners' perceptual distinction of the two sounds. This suggests that small differences in the articulation of these sounds can have a perceptual impact on the acoustic output.

However, as noted for children above, sibilant variability is often seen as a result of coarticulatory effects. Most of the literature suggests that sibilant fricatives are stable articulations that are resistant to coarticulatory effects, following the Degree of Articulatory constraints model (DAC), where some consonants show low resistance to coarticulation than others (Recasens, 1997; Dagenais, Critz-Crosby & Adams, 1994; Ladefoged & Maddieson, 1996; Tabain, 2001). The voiceless sibilant fricatives have both been allocated a high DAC value (reflecting the precise positioning of the tongue required for perceptually acceptable productions) (Recasens, Pallarès & Fontdevila, 1997). Though it has since been argued that /s/ is less resistant to coarticulatory effects than /ʃ/ (Pouplier, Hoole & Scobbie, 2011), explained by the agility of the tongue tip/blade in /s/ in comparison to the less agile tongue dorsum in /ʃ/ (Zharkova et al., 2012). It has already been mentioned that /s/ is retracted in presence of /r/ (/str/ clusters) (Baker et al., 2011) but Ultrasound data from Zharkova et al. (2012) has provided evidence of sibilant articulation differences in differing vowel contexts. These findings indicate that spatial variability in sibilant production does occur in typical adult speakers, though perhaps not to the extent noted in other articulations (e.g. /p/, see Zharkova, Hewlett, Hardcastle & Lickley, 2014).

In addition, within-speaker variability in sibilant production has been identified in studies of the post-alveolar sibilant, indicating a range of articulations for similar acoustic outputs. This is termed *motor equivalence* (Hughes & Abbs, 1976). In typical /ʃ/ production it has been established that lip protrusion and constriction position can have a compensatory relationship which impacts on spectral frequencies (Brunner & Hoole, 2012; Perkell et al., 2000). Listeners are able to identify acceptable productions of /ʃ/ when the tongue is in an anterior position if there is increased lip protrusion, and vice versa. Therefore, although considered highly stable articulations, in the case of the post-alveolar sibilant there are different articulatory configurations that a speaker may use for a single acoustic output.

The above studies suggest that the articulations produced for perceptually acceptable sibilant productions can be variable (particularly in relation to tongue position) in typical speakers. However, they are less susceptible to adaptations than other sounds. As a group with speech motor difficulties it is suggested that sibilant production in DS would not show the typical levels of articulatory stability, and that within-speaker variability in articulation would be higher than reported in typical speakers.

2.4.7 Typical development of sibilants

Sibilants are acquired later on in normal speech acquisition (see Table 2-1) than homogenous plosive sounds (Robb & Bleile, 1994; Shriberg, Kwiatkowski & Gruber, 1994; Stoel-Gammon, 1985). When considering the typical course of acquisition for these sibilants, most of the literature focuses on impressionistic phonetic transcription, with rather less acoustic analysis, and almost no articulatory investigation.

Often the difficulty interpreting acquisition data lies in the different methodologies used by the larger acquisition studies in the literature. Sander (1972) highlights the problems with comparisons of studies with the example from Templin's (1957) study (data shown below). In Templin's study phonemes were included once 75% of children had mastery of the sound in WI, WM and WF positions. However, Sander (1972) notes that in Templin's data, all children at age 3 could produce /t/ in word initial position (75% of children managed this in word final position), yet the age of acquisition is given as 7;5 (this is not used for information provided in Table 2-2). The evidence from these studies suggests that the sibilants are acquired (produced in a perceptually acceptable way at least 75% of the time) later than /t/ but there is a lack of agreement for acquisition of /s/ and /ʃ/. Shriberg et al. (1994) established broad categories of early- middle- and late- developing consonant sounds in English phonological development and suggested that /s/ and /ʃ/ belong to the later acquired group of consonants but provides no distinction between the two.

Target consonant	Templin (1957)	Smit et al. (1990)	Grunwell (1982)
/t/	3;0	3;6	2;0-2;6
/s/	4;6	7;0-9;0	2;6-3;6
/ʃ/	4;0	7;0	3;6-4;6

Table 2-2: Typical ages of acquisition: /t/, /s/ and /ʃ/ from three acquisition studies

Stoel-Gammon (1985) recorded 34 children longitudinally from 9 months until 24 months. The children were recorded at 3 month intervals during play sessions at home. From analysis of consonant sounds produced at the recording intervals, Stoel-

Gammon notes that in word initial position primarily stops, nasals and glides are produced (voiced and anterior). At 24 months the inventories show productions of posterior sounds, and particularly, voiceless fricatives. Within her data, Stoel-Gammon finds that there are individual variations in phoneme development but they are minor within the general pattern. This contradicts other findings which indicate substantial variation in infant development, though Stoel-Gammon suggests that this could be a result of experimental design (in her study, small speech samples were used). Robb and Bleile (1994) analysed emergence of consonants in young children noting that /s/ emerged in WF position initially around 18 months, with WI appearing at 24 months. /ʃ/ had not appeared at 24 months in their 7 children. In their study of 360 typically developing children, Kenney and Prather (1986) found that at age 2;5 boys and girls had more errors in /ʃ/ production than /s/ production. Dodd, Holm, Zua and Crosbie (2003) sampled speech from 684 children and (using a 90% level of acquisition) found that /s/ was acquired at 3;0-3;5 years and /ʃ/ at 5;0-5;5 years.

Therefore we find that there are discrepancies in the reporting of the emergence of these consonants. However, the literature somewhat agrees that typically /s/ appears before /ʃ/ (Dodd et al., 2003; Smit et al., 1990). Common typical errors in target sibilant production in English speech sound development are: stopping of /s/ to /t/, /ʃ/ is initially stopped to /t/ then fronted to /s/ (Grunwell, 1982, Li et al, 2009). Smit et al. (1990) found that the common error of stopping of /s/ occurred in typically developing children between the ages of 2 and 5 years. They also noted presence of dentalisation (where the tongue makes articulatory contact with the teeth, ranging from interdental /s/, /θ/, to slight dentalisation) throughout all ages, but the occurrence of these errors decreased by age. Dentalisation is a common distortion of /s/, and is often transcribed when the tongue makes contact with the teeth during /s/ production (Shriberg & Kent, 2013). Both dental fricatives and alveolar sibilants involve lateral bracing, but the dental fricatives are produced with a flat tongue compared to the groove tongue constriction of /s/ and /z/. Smit et al. (1990) also noted some evidence for lateralisation of /s/, but this was very low across all ages.

In their instrumental study of sibilant acquisition in 2 and 3 year olds, Li et al. (2009) found that children go through an unstable articulatory phase when establishing the /s/~/ʃ/ distinction. They noted that target /ʃ/ productions showed spectral differences to target /s/ production, even though they were perceived to be [s]-like, suggesting a covert contrast stage of development. These findings suggest that the acquisition of typical sibilant articulation is not yet fully understood.

2.4.8 Sibilant production in disordered populations

As later acquired sounds, the alveolar and post-alveolar sibilants are frequently impaired in disordered populations (Fletcher, 1985; Gibbon, 2004; Fuchs, Brunner & Busler, 2007). Errors are commonly noted in studies of speakers with hearing impairment, Dysarthria, cleft palate, DS and Apraxia of Speech. In a review of cleft palate articulation difficulties, Harding and Grunwell (1996) note that most studies find /s/ the most often misarticulated consonant in this population (with three of the six they reviewed noting /ʃ/ a close second). These findings may suggest that /s/ is identified more in error than /ʃ/ for other speaker groups, which may explain the high number of studies reporting on the alveolar sibilant but small number including the post-alveolar sibilant. The majority of perceptual analyses of sibilant misarticulations note that these sounds are generally omitted, and substituted. Common atypical substitutions for /s/ have included, dentalisation (e.g. [s̪], though Daniloff, Wilcox and Stevens (1980) also note that this rarely may extend to [θ]), lateralisation, and lisping (Daniloff, Wilcox & Stevens, 1980; Brunner, Hoole & Perrier, 2011). Daniloff et al. (1980) provide 3 categories of atypical sibilant error: dentalisation, lateralisation and other (those not dental or lateral). A simplistic 3-way division of articulation error cannot be considered adequate for description of these complex articulations and Gibbon and Hardcastle (1987) note that clinicians are more likely to refer to atypical placement differences in disordered /s/ production, using terms relating to positioning, i.e. dental, lateral, palatal, retracted, rather than traditional terms such as lisping.

More information about the error types produced for target fricatives in disordered populations can be found using instrumental techniques but there are few studies in the populations mentioned above. Chen and Stevens (2001) assessed word-initial /s/ in speakers with dysarthria and found that certain acoustic parameters correlated highly with the speakers' overall intelligibility. These were: measures of deviation from the norm in the time variation of the acoustic pattern within the consonant and across the consonant-vowel boundary and spectrum shape of the friction noise. Studies have also analysed fricative production in Aphasia (Code & Ball, 1982; Haley et al. 2002; Harmes et al., 1984; Wambaugh, Doyle, West & Kalinyak, 1995) and amyotrophic lateral sclerosis (Tjaden & Turner, 1997). Similarly to perceptual based analyses, instrumental studies are usually focussed on /s/ production but studies into disordered productions of /ʃ/ are lacking. Although the reasoning for this is not clear from the literature available, it may be due to the supposed complicated acoustic and articulatory nature of the post-alveolar sibilant.

Articulatory techniques have increased awareness of articulation errors in sibilant production. Goozee, Murdoch and Theodoros (2003) analysed (alongside other consonants) the alveolar sibilants in 3 males with dysarthria. They analysed the location and pattern of tongue to palate contact, specifically the narrowest part of the groove (width and length of constriction). They noted increased contact and complete closure which they attributed to the lack of neuromuscular control in their subjects. Hardcastle, Morgan Barry and Clark (1987) studied (among others) target alveolar sibilant articulation in articulation-disordered children and found velar contact in 3 of their 4 speakers. EPG studies of fricative production in disordered speech populations will be discussed in more detail in 662.5.4.

Fricatives are therefore an interesting articulatory area of study and are speech sounds frequently in error in many different speech disordered populations, and also in DS (Roberts et al, 2005). Chen and Stevens (2001) provide a concise list of actions involved in the production of word initial /s/ that may be difficult for individuals with neuro-motor disorders. These are:

> "(a) proper positioning of the tongue body (as distinct from the tongue blade) to yield appropriate transitions of the formants into the vowel, particularly the F2 transition);
>
> (b) shaping of the tongue blade so that the airstream is directed against the lower incisors;
>
> (c) raising the mandible to position the lower incisors to form an obstacle for the airstream, and maintaining this position during the fricative;

(d) spreading of the glottis so that the vocal folds do not vibrate and there is appropriate pressure in the oral cavity;

(e) coordination of the decrease in glottal spreading and the release of the tongue-blade constriction as the fricative ends and the vowel begins;

(f) motion of the articulators at a proper rate following the release of the consonant; and

(g) in the case of an utterance-initial fricative, coordination of the respiratory pressure and the positioning of the glottal and supraglottal articulators" (2001; 1303)

Of those actions presented above, Chen and Stevens (2001) suggest that any deviations from these settings can result in deviant productions of /s/. In the case of a speaker with DS, all of these would be problematic for speakers with presence of hypotonia, small palate shape and speech motor deficits.

2.4.9 Sibilant production in children with Down's syndrome

As noted in section 2.3.2.2, studies have detected difficulties with the production of fricative sounds in children with DS (Cleland et al., 2010; Dodd, 1976; Roberts et al., 2005; Rondal, 2009; Rondal & Edwards, 1997; Rosin et al., 1988; Sokol & Fey, 2013; Wood et al., 2010). In studies of young children (3 to 6 years) with DS, stops and nasals have been found to be produced correctly but problems with fricatives (also affricates, glides and laterals) are common (Bleile & Schwartz, 1984; Stoel-Gammon, 1980). In a wider age group of 32 children (4-14 years) with DS, Roberts et al. (2005) analysed the production of early, middle and late acquired consonants and found that the early consonants were produced more correctly than the middle and the middle produced (significantly) more correctly than the late acquired consonants (/ʃ ʒ θ ð s z l r/). Many of the instrumental studies reviewed in 2.3.2.3 have also identified errors in sibilant production in speakers with DS.

2.4.10 Effects of Down's syndrome on sibilant production

The following subsection looks at the different features of DS introduced in section 2.2 and considers the impact these differences may have on the successful production and development of sibilant production.

From the information gathered on sibilant production it is clear that these are complicated articulations that require a stable, controlled articulation that can route airflow precisely, through narrow channels and cavities. The sibilant fricatives can be acoustically dependant on dentition as well as finely-tuned active articulators. All these features are likely to be difficult in speakers with DS due to the anatomical, structural and motoric problems this population faces.

2.4.10.1 Structural differences and sibilant production

The relationship between speech and oral cavity structure is not straightforward. Palate shape defects and different dentitions have all been found in speakers with articulation difficulties, not just restricted to people with DS. However, speakers have the capacity to compensate for these structural differences and not all speakers with errors in fricative production have anatomical differences. Bleile (2002; 248) suggests that due to the high levels of flexibility in the speech mechanism, only "gross abnormalities interfere with speech production". As suggested in 2.2.2.1, it may be hypothesized that people with DS experience such "gross abnormalities", for example the shorter and narrower palate affecting tongue placement, along with the larger tongue in relation to the smaller oral cavity.

As noted in 2.2.2.1, establishing a relationship between anatomical oral structures and the propensity of articulation difficulties is complex. However, there is some evidence to suggest that articulation may be disrupted. For example, Oliver and Evans (1986) found that typical speakers with more articulatory defects had smaller oral dimensions which may affect accurate placement of the tongue during articulation. It is unclear, however, what type of articulatory defects the typical participants presented with, as this study fails to provide detailed speech information. Additionally, they only report on trends noted in their data.

More recently, the impact of anatomical differences on typical articulation variability has been investigated. The majority of these studies have reported on vowel articulation variability in relation to flat and domed palates, suggesting that a larger space (i.e. domed palate) results in higher variability (Brunner et al., 2009). However, similar studies have yet to agree that structural differences can affect articulation of sibilant production (Perkell et al., 2004; Weirich & Fuchs, 2013).

An earlier study by Laine (1986) presented a large study of palatal measurements and auditory analyses of /s/ productions in typical Finnish adults. Results identified a significant relationship between speakers with defective /s/ (described as produced more posteriorly) showing a tendency to have a slightly narrower palate and a shorter palate than normal. Laine suggests that distortions are high in speakers with narrow palates due to lack of space for movements of the tongue. Laine's data is provided from typical adults who present with sibilant distortions, however there no detail of these distortions is presented. However tentative this link may be, Laine's conclusion may be particularly relevant for speakers with DS who present with a normal sized tongue but small oral cavity.

Palate shape and size may have an impact on speech articulation in people with DS but articulatory compensations are common in people with structural differences. Compensations, however, may be complex to achieve if hypotonia and speech motor control is also affected.

2.4.10.2 Dentition and sibilant production

The link between dentition and speech production is still not firmly established, although studies have attempted to resolve this issue for many years. The majority of studies investigating this link are old, and provide either no, or very tentative links between dentition and articulation. For example, Bernstein (1954) assessed the presence of malocclusions in 437 children with speech disorders, and 446 children with normal speech patterns. He found that the children with speech disorders did not have a greater amount of malocclusions than the control group. Other early studies agreed with Bernstein (Frowine & Mosser, 1944; Hopkin & McEwan, 1956; Rathbone, 1955) and more recent research (Lopez-Perez et al., 2008; Oliver & Evans, 1986) also found that dentition does not have a significant effect on speech articulation (e.g. Hopkins and McEwan (1956) found as many speech defects in speakers with normal occlusions compared to those with malocclusions). The lack of a causal link could be explained by the presence of the many other variables involved in articulation, and the methodological difficulties in isolating dentition as an obstacle to successful speech. However, if we look only at studies of dental malocclusions and sibilant production contrary evidence appears.

Shadle (1990) states that in the production of the sibilant fricatives the noise is created when the constricted airflow collides with the incisors. Perkell et al. (2004) found that speakers who produce /s/ with lingual contact on the lower teeth and /ʃ/ without have the clearest distinction between the two. The role that dentition plays in the production of the sibilant fricatives suggests that dental malocclusions should have some degree of impact on their successful production but it is uncertain the extent of that impact. Again the studies investigating a relationship between dentition and sibilant production are mostly old, though some more recent information has been gained through vocal tract modelling.

In his study of speakers with articulation disorders, Laine (1987) found a significant relationship between the presence of anterior open bite and distorted productions of /s/. He suggests that the open bite is not itself impacting on the successful articulation of /s/ in his speakers, but the orofacial structure related to this dentition type. The errors noted in this study were almost all anterior productions with the tongue protruding (perceived as [s̪], or occasionally interdental [s]), therefore providing evidence of lingual placement distortion as a result of anterior open bite. Consequently, Laine’s study does not investigate the impact dentition differences would have on the perception of sibilants if the lingual articulation was correctly placed. Similarly, Warren, Nelson and Allen (1980) assessed the impact of open bite size on production of sibilants and found that at certain heights the opening was too large to maintain the intra-oral pressure required for production of the sibilant fricatives. They also suggested that the open bite structure may impact on the successful development of a centrally grooved tongue configuration, once again providing a link between tongue placement and anterior open bite. The relationship between sibilant production and open bite is more established than the impact of the Class I-III malocclusions, however, Guay, Maxwell and Beecher (1978) found that 11 out of 12 adolescents with Class III malocclusions misarticulated /s/, even when speakers attempted to compensate for their structural differences (by adjusting jaw and tongue position). More recently Lee, Whitehill, Ciocca and Samman (2002) assessed /s/ production errors in speakers with malocclusions before and after orthognathic surgery to reset the malocclusion. They note that all speakers with fricative errors before surgery showed a decrease in the number of errors after surgery suggesting that the malocclusion had some impact on perceptual acceptance.

Both anterior open bite and Class III malocclusions are commonly found in people with DS (e.g. over 50%, though see section 2.2.3 above) so we may assume that dentition could be a contributing factor in the misarticulations of sibilant productions in this group. However, not all speakers (both typical and those with DS) with dental deformities experience articulation difficulties (e.g. over 50% of Lee et al.'s participants presented with no perceptual fricative errors before surgery). This suggests that differences in dentition may play a part, but may not explain, the articulation difficulties children with DS experience.

2.4.10.3 Hearing loss and sibilant production

Due to the acoustic characteristics of fricative sounds, perception and production of these segments can be difficult for speakers with hearing loss. For the sibilants this is particularly relevant as the perceived differences are at high frequencies. Moeller et al. (2007) found that overall consonant development was delayed in children with sensorineural hearing loss compared to age-matched children without hearing loss. Importantly they noted atypical development patterns in fricative and affricate development. Stelmachowicz, Pittman, Hoover and Lewis (2002) reviewed studies of phonological development and found delayed phonological development (particularly long in fricatives) in children with hearing impairment. McGowan, Nittrouer and Chenausky (2008) compared the speech production of children at 12 months with and without hearing loss, and also identified a delay in consonant production (with less fricatives produced in the hearing loss group). In their study of post-lingual adults with sensorineural hearing loss, Lane and Webster (1991) noted that three male speakers maintained a phonemic differentiation between the alveolar and post-alveolar fricatives, but this was less acoustically distinct than age and gender matched control subjects (with the post-alveolar sibilant being produced further forward). They conclude that their speakers have produced a "systematic error in phonetic implementation" (1991; 865).

A causal link between hearing loss and successful production of sibilants is not suggested by the studies above. However, more concrete links are provided from instrumental phonetic studies. In an EPG study, McGarr, Raphael, Kolia, Vorperian and Harris (2004) found that the amount of lingual-palatal contact for /s/ and /ʃ/ in three speakers with hearing loss was much greater than control speakers, suggesting that hearing loss affects precise articulator constriction. Similarly, in an acoustic study of adults (n=107) with hearing loss, Koch and Janse (2011) found that articulatory precision of sibilant productions was lacking in adults with mild hearing loss. These studies suggest that hearing loss has an impact on precise articulation of sibilants, but does not seem to suggest that speakers present with categorical errors.

Similar findings have been identified in a series of papers specifically investigating the importance of auditory acuity (alongside somatosensory feedback) in the perception and production of the /s/ ~ /ʃ/ contrast. Perkell et al. (2004) have suggested that speakers with higher auditory acuity produce clearer contrasts between the aforementioned sibilants. Work from the same team with post-lingually deafened subjects has identified increased contrasts between /s/ and /ʃ/ post cochlear implantation (Matthies et al, 1994; Lane et al, 2007), suggesting that auditory feedback encourages the articulatory distinction. Furthermore, Ghosh et al (2010) note that high levels of within speaker variability are related to auditory acuity, suggesting that not only precision, but articulatory variability, is affected by hearing loss. These findings support previous suggestions that hearing loss may impact sibilant articulation.

As noted above, auditory deficits are found to impact on speakers' articulatory distinction of sibilant production. It may be suggested that the high presence of hearing loss in speakers with DS will affect the articulatory precision required for sibilant production.

2.4.10.4 Speech motor control and sibilant production

As noted earlier, speech motor deficits have been identified in speakers with DS through various measures (see section 2.2.5.3). Speech motor control abilities have been found to have a wide impact on speech intelligibility (Namasivayam et al., 2013) and recently Weismer, Yunusova and Bunton (2012) reported that tongue control (rather than lip-jaw control) is strongly related to speech intelligibility. Considering the complex articulatory coordination involved in sibilant production, we would expect speakers with speech motor deficits to experience production difficulties. These complex articulations put high demands on the speech motor system and unsurprisingly are often misarticulated in speech motor disorders (Chen & Stevens, 2001).

Bunton and Leddy (2011) and Bunton et al. (2007) suggest that oral-motor difficulties play an important part in the speech problems in DS. However, it is unclear what the specific difficulties are with sibilant production in this group and how those difficulties may relate to motor control problems. The impact of speech motor deficits, as experienced by children with DS, may affect the controlled narrowing and stabilisation of the tongue required for successful frication. As noted in 2.2.5.3 there is a lack of evidence for speech motor difficulties in children with DS, and further investigations are required.

2.4.10.5 Summary: Effects of Down's syndrome on sibilant production

There is evidence to suggest that sibilant production in DS is likely to be impaired as a result of structural differences, hearing loss and speech motor deficits. The specific nature of the difficulty with sibilants in DS may be speaker-dependant, but may relate to some of the areas mentioned above. Considering again the points identified by Chen and Stevens (2001; 1303) regarding successful sibilant production, it can be expected that the motor difficulties experienced in children with DS may affect "(a) proper positioning of the tongue body (as distinct from the tongue blade) to yield appropriate transitions of the formants into the vowel, particularly the F2 transition)". Success here may also be related to the palate shape, which, along with motor difficulties, could also have an impact on, "(b) shaping of the tongue blade so that the airstream is directed against the lower incisor". With high numbers of children with DS presenting with dental malocclusions, mandible positioning and control may be problematic for children with DS, affecting their success in "(c) raising the mandible to position the lower incisors to form an obstacle for the airstream, and maintaining this position during the fricative". Of the other points raised by Chen and Stevens (2001), (d) (e) and (g) relate to laryngeal gestures that may be problematic for children with DS, but are not included in this particular study. However, "(f) motion of the articulators at a proper rate following the release of the consonant" may be problematic in children with DS experiencing speech motor difficulties.

2.4.11 Summary: Sibilant production in typically developing children, adults and people with Down's syndrome

Sibilant fricatives are included in this study particularly as they are frequently problematic for children with speech disorders (often appearing as residual speech sound errors), and in children with DS. Therefore, it is considered that these particular target sounds would present with many errors in this experimental group. In section 2.4.8 above, it has been argued that differences in people with DS would have a negative impact on successful sibilant production, particularly hearing loss, palatal shape, tongue size and speech motor difficulties. While this study does not have the scope to provide detail on the anatomical differences of these children, it can provide a detailed articulatory investigation of speech abilities in this group in order to identify speech motor problems. As established, sibilants are complex articulations that are considered invariant and resistant to contextual effects, with small articulatory changes possibly creating a large phonemic contrast (Lindblad & Lundqvist, 1994). As noted in 2.2.5.3, within-speaker speech variability in typical children has been noted to be related to speech motor abilities. Therefore a set of typically invariant speech sounds would be a highly suitable dataset for investigations of speech variability. The complex lingual articulations involved in sibilant production also lend these speech sounds to investigations via articulatory techniques. It is proposed that in order to investigate sibilant production properly the articulatory analysis technique, EPG can be employed as it provides detailed information about phonetic aspects of articulation. In addition to information regarding lingual-palatal contact, measures of spatial variability (via EPG indices) can provide an insight into speech motor abilities linked to speech articulation (Howell, Anderson & Lowit, 2011). Furthermore, EPG is particularly suited to the investigation of sibilant production, as it provides means to measure the lingual groove pattern discussed above (2.4.5), and to investigate spatial and temporal variability.

2.5 Electropalatography (EPG)

Auditory analysis of speech data is the most prevalent form of analysis in both normal and disordered speech populations. Auditory phonetic transcription is used in clinical analysis as it is the only way to establish the "effect an individual's speech impairment has on his or her spoken communication and intelligibility" (Heselwood & Howard, 2008; 382). While this can be subjective, it provides an overall impression of the speaker, which can also highlight areas of difficulty suitable for further investigation. Where we find limits to auditory transcription is when we wish to objectively measure aspects of the speech being analysed. In this case, auditory analysis is limited as it provides "an indirect representation of the actions of the articulators, with the result that articulatory information must be inferred by the transcriber" (Gibbon, 1999; 383). As highlighted by Wood and Hardcastle (2000), limitations can range from preferences for phonemic categorisation, variation of individual transcribers and the 'phonemic restoration effect' (Warren & Obusek (1971) cited by Wood & Hardcastle (2000; 205)), where the knowledge of the target sound can influence the perception of speech sounds. Kerswill and Wright (1999) also suggest that auditory analysis may be influenced by the transcriber's knowledge of the particular dialect, and even the particular speaker focus on transcriber variation. They further suggest that transcribers can differ in their approach to the task of auditory transcription, arguing that transcriptions can either represent articulations or auditory impressions. Although Kerswill and Wright (1999) consider these approaches problematic, and particularly difficult to interpret, they still endorse the use of auditory transcription, but alongside instrumental techniques. It is often the case that auditory analysis of clinical speech data is supported by instrumental measurements (Amarosa, von Benda, Wagner & Keck, 1985). As demonstrated by Howard and Heselwood (2011), perceptual analysis should be utilised to both support instrumental analysis of speech and also represent the perceptual effect, providing a listener perspective.

For the analysis of sibilants, the acoustic representation is commonly studied, as spectrographic information can identify place of articulation and presence of lip-rounding (Jongman et al., 2000). However, acoustic analysis cannot provide the precise information regarding the articulation of speech sounds that articulatory techniques can. In the case of the sibilant fricatives, this involves the shape and size of the narrow groove constriction. Additionally, similar acoustic patterns do not necessarily result from the same articulatory movements (Perkell et al., 2000). Articulatory analysis techniques such as EPG and Ultrasound have recently provided objective and quantifiable representations of the tongue during speech production. Though slightly more invasive than Ultrasound, EPG is more suited to studying the groove configuration involved in sibilant production than Ultrasound as it can provide information regarding the precise contact involved by the tongue in relation to the palate. Therefore EPG is particularly suited to sibilant analysis as the groove width and length is easily identified (Hardcastle & Edwards, 1992).

2.5.1 EPG analysis of speech production

EPG has its roots in palatography which provides a visual representation of tongue contact with the palate. It is a technique that records the timing and location of tongue contact with the roof of the mouth during continuous speech production (Hardcastle, 1984; Hardcastle, Gibbon & Jones, 1991). The user is required to wear a custom-made artificial acrylic palate which is embedded with electrodes, positioned in 8 rows and 8 columns. The electrodes are 1.4mm in diameter and are connected to a thin copper wire. The wires from each electrode are embedded into the acrylic palate and exit in a bundle at the posterior corners of the palate (Hardcastle et al. 1991). The wires combine on a board which is inserted into a multiplexer unit worn around the speaker’s neck. During speech recording, the speaker holds an electrode providing a small sinusoidal signal (Hardcastle & Gibbon, 1997). Once set up, tongue contact with the touch-sensitive electrodes completes an electrical circuit. Lingual-palatal information is recorded from this contact with the electrodes every 10 milliseconds via the multiplexer, which contains circuits that amplify signals from the electrodes. These patterns of contact are then recorded on a normalised computational representation of the acrylic palate for storage and analysis (see Figure 2-1).

The EPG palate is manufactured for each individual speaker from an upper dental impression. Based on the dental impression, the palate is then moulded to the shape of the roof of the mouth. This allows the creation of a palate that sits closely to the speaker's upper oral cavity, securely, during continuous speech, without interference to normal speech production.

The EPG system used for this project is the WinEPG™ system, designed by Articulate Instruments Ltd, which requires specialised software to present and analyse the lingual-palatal contact. Articulate Assistant (AA) is widely used with the WinEPG™ system around the world and allows the user to view the EPG palate frames alongside acoustic information. The user can also set a range of automatic measures that will calculate the amount of contact at various points on the palate.

Using the EPG hardware and software, the EPG palate registers tongue-palate contact and characteristic patterns are identifiable from that contact. In English this includes the plosives /t, d, k, g/, the sibilants /s, z, ʃ, ʒ/, affricates /ʧ, ʤ/, the palatal approximant /j/, lateral /l/ and the nasal sounds /n, ŋ/. Vowels and diphthongs also show some characteristic tongue-palate patterns, but only the close vowels and diphthongs with close off-glides (Gibbon, 1999).

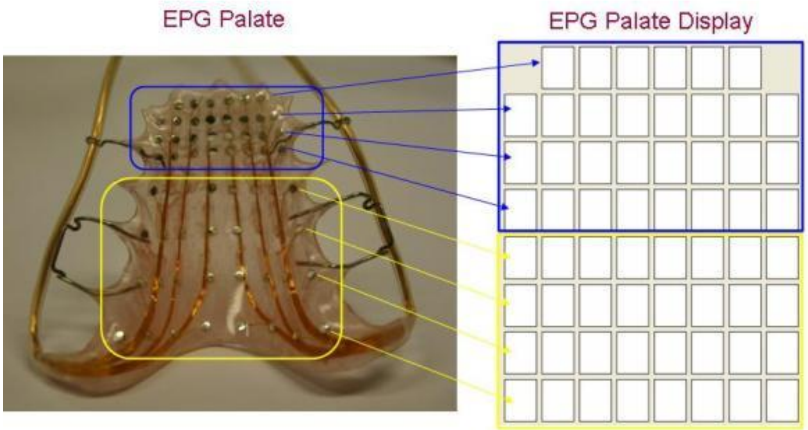


Figure 2-1: EPG palate highlighting electrode positions and the relationship with the computerised EPG palate frame (right). Blue highlighted section represents anterior section of the palate, yellow is the posterior

The electrodes are set in the palate according to anatomical landmarks (Wrench, 2007) relating to places of articulation. The first four rows (blue in Figure 2-1 above) of the palate make up the anterior part (concentrated around the alveolar ridge) and the next four rows (spread out over the hard palate and velum, yellow in Figure 2-1), the posterior part. For this study, the anterior section of the EPG palate is taken to reflect the alveolar and post-alveolar places of articulation and the posterior section of the palate represents the palatal and velar places of articulation. The electrodes in the front 2 rows are set closer to each other than those in rows 3-4, which in turn are closer than the posterior electrodes in rows 4-8. This spacing and subsequent normalisation on the computerised image needs to be considered when interpreting EPG pattern analysis. The computer generated EPG frames represent each electrode with a rectangle that can be either on or off (registering tongue contact or not), this is coloured black if there is tongue contact.

2.5.1.1 Limitations of EPG

EPG is a useful instrumental technique capable of providing information on speech articulation that has previously been difficult to obtain quantitatively (i.e. exact position of tongue-palate contact) however there are limitations.

2.5.1.2 The EPG palate

The palate itself is problematic as it is ultimately a new obstacle in the oral cavity which (without preparation) will affect the acoustic result of articulation. However, speakers are able to produce natural speech with the palate in place by wearing the palate in advance for a short period of time (McAuliffe et al., 2008; McLeod & Searl, 2006; Searl, Evitts, & Davis, 2006). The use of EPG is less usual with small children as their dentition is not mature enough to allow the palate to stay in place. It also may be uncomfortable for children (and sometimes adults) to get a dental impression made, especially as an impression produced for EPG needs to extend further back than usual to allow for velar contact to be recorded.

EPG palates are expensive to produce and, in the case of children, may only be used for a short period of time depending on changes to dentition, and oral cavity shape and size. For adult speakers, dentition and other oral cavity changes will also have an impact of the continued use of the palate. New methods are constantly being considered to produce an EPG palate which is flexible, thinner and cheaper to manufacture.

2.5.1.3 Data recording

EPG records tongue-palate contact but will not provide evidence on tongue shape, or the part of the tongue involved in the articulation. It is limited in the analysis of vowels, particularly the open vowels; though some contact is clear in the relatively close vowels (i.e. /u/ and /i/) (see Bacsfalvi et al., 2007; Gibbon, Lee & Yuen, 2010).

The EPG recording will only provide lingual-palatal contact. No information is therefore available on the oral/nasal airflow distinction or the activity of the vocal folds. As the EPG palate is custom-made to fit onto a dental impression this limits the analysis to the area covered by the palate. In most speakers of English, the EPG palate does not extend to the exact velar place of articulation so that velar stops do not show complete closure at the back of the EPG palate. This is not to suggest that the speaker does not achieve complete closure, but is commonly due to the EPG palate not reaching the velar place of articulation. Speakers can also create lateral contact/closure with the teeth which are also outside of the EPG palate region. Additionally, EPG patterns of contact can only provide information regarding tongue placement, not tongue pressure or information regarding tongue shape. All these things should be kept in mind when analysing speech production using EPG.

2.5.1.4 Data Reduction measures

EPG analysis involves the transformation of lingual activity, as placed on the roof of the oral cavity, to a computerised representation of the embedded electrodes. The accurate spacing of the electrodes is lost when visualising articulation patterns via AA software, as the electrodes are transferred to a standard grid pattern (see Figure 2-2). Most articulation analysis using EPG is obtained from a variety of numerical indices that capture the amount and location of lingual-palatal contact. The researcher has a certain degree of freedom in the range of calculations to perform and the detailed parameters of these calculations. The most common measures are Centre of Gravity (COG), amount of palatal contact, spatial and temporal variability and closure measures.

There may be problems relating the regions of the computer frame to the actual speaker palate, considering the variability in palate shape and size within the typical speaker (not to mention the difficulty applying these placement landmarks to the atypical palate). This is of particular concern when using EPG with speakers who have known palatal size and shape differences (e.g. DS).

2.5.2 EPG characteristics of lingual consonants

The dynamic representation of speech provides a useful platform for spatial and temporal measurements of speech. EPG can support perceptual analysis of speech production and also provide information on articulation information that is otherwise hidden, for example the closure phase of a plosive sound, the size of the tongue groove during coronal sibilants.

During the production of consonants, place of articulation is one of the main features of production (alongside manner and voicing). EPG is able to provide information about the tongue position during consonant production by registering lingual-palatal contact. Although the place of articulation can clearly be identified using EPG, the part of the tongue used in this contact is not observable. However, as noted in Gibbon (1999) it is possible to infer what part of the tongue is involved. For example, when the contact is in the anterior part of the palate the tongue tip/blade will be used (implying that no distinction is possible between the anterior sections of the tongue), if the contact is in the posterior part of the palate then the tongue body will be used. An added element of articulatory information from EPG is the clear evidence of lateral contact that arises during the production of various lingual-palatal consonants (plosives and sibilants).

While there is a degree of variability in speech production there are still standard articulation patterns for the speech sounds studied by EPG so far. Figure 2-2 below shows standard patterns for common English consonants produced with lingual-palatal contact. For the alveolar stop consonants, a horseshoe shape of contact is produced, with complete tongue contact at the anterior part of the palate, alongside lateral bracing (completing the seal required for the plosive sounds). The alveolar sibilant consonants /s/ and /z/ are produced with lateral contact on both sides of the palate and increased contact at the first two rows. The anterior contact is not complete, as a small opening is evident from the grooving of the tongue. The post-alveolar sibilant shows a similar pattern to the alveolar sibilants, but the narrowest part of the groove (and area of most contact) is at the 3rd and 4th rows of the palate (representing the post-alveolar region of articulation).

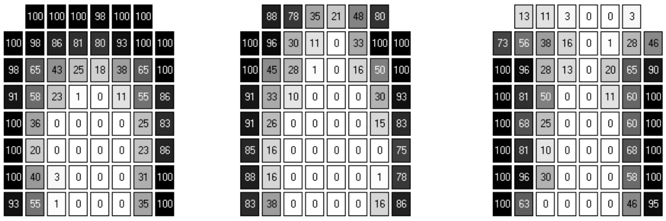
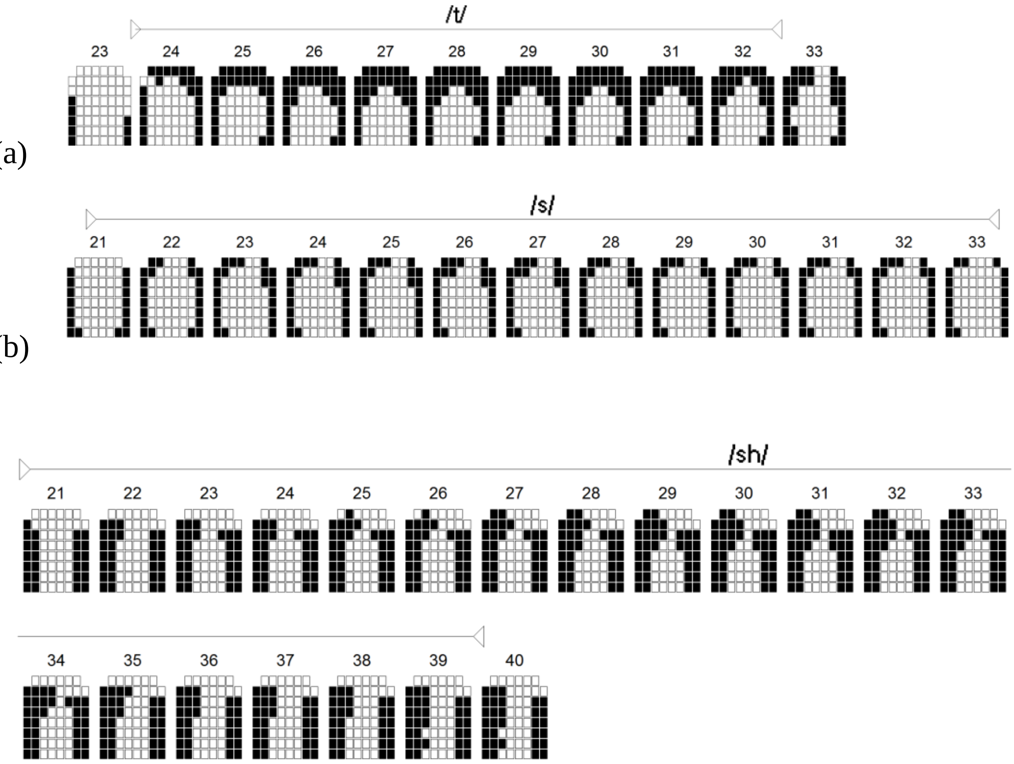


Figure 2-2: Average EPG contact patterns for adult English productions of alveolar stops, alveolar sibilants and post-alveolar sibilants from first frame of maximum constriction. Numbers present percent contact for each electrode.

EPG also allows the visualisation of the dynamic pattern of articulation across the constriction. For the alveolar stop, this represents the hold phase of the plosive. The alveolar and post-alveolar sibilants show narrowing at the onset of the groove articulation, and then widening at the offset (see Figure 2-3 for examples).



(a)

(b)

(c)

Figure 2-3: Examples of dynamic EPG frames for (a) /t/ produced in the word ‘toe’, (b) /s/ produced in the word ‘sun’, and (c) /ʃ/ produced in the word ‘sheep’ by a typical Scottish English adult speaker.

2.5.3 Typical speech analysis with EPG

EPG has provided a means to investigate many different aspects of articulation in typical speech production. Most studies have investigated adult articulation patterns, providing only small numbers of participants. However these small studies have provided valuable phonetic information on articulatory behaviour of consonants and vowels from a variety of languages (e.g. Croatian: Liker & Gibbon, 2007; Catalan: Recasens & Espinosa, 2007; German: Mooshammer, Perrier, Fuchs, Geng & Pape, 2004; Swedish: Lindblad & Lundqvist, 1994), aspects of coarticulation (Butcher, 1989; Guzik & Harrington, 2007; Zharkova, 2007), and increased our understanding of gestural timing (Hardcastle, 1985; Wood, 1997). Regarding consonant articulation, English adult articulation patterns have been the focus of work by McLeod and colleagues (McLeod, 2006 (n=7); McLeod, Roberts & Sita, 2006 (n=10); McLeod & Singh, 2009) who provided information on lingual fricatives (see section 2.5.3.1 for EPG investigations of sibilant fricatives) and the alveolar nasal. For typical EPG patterns, McLeod and Singh (2009) present the most comprehensive published guide to consonant articulation patterns in varieties of English, reflecting between- and within-speaker variability from 8 adult speakers (the same speakers are presented in McLeod, (2006)). Some of these patterns have been replicated here (Figure 2-4 and Figure 2-5). Further work has provided typical adult data on specific articulations, e.g. Liker and Gibbon (2008) focussed on the velar stop in English adult speakers though like many of the aforementioned studies, investigated a small number of participants (n=7); McAuliffe, Ward and Murdoch (2002) presented EPG data from 10 adult speakers for /t/, /l/ and /s/. Not all typical EPG studies have concerned lingual speech sounds, Gibbon, Lee and Yuen (2007) analysed lingual patterns during bilabial targets (again in a small number of speakers, n=8) and noted presence of lateral lingual palatal contact. In their detailed investigation into between-speaker differences, Gibbon and Lee (2011) were able to highlight the importance of individual differences when analysing and interpreting EPG measurements from typical adults (n=7) and children (n=4). Further work by Lee, Gibbon and Oebels (2014) identified dynamic patterns of lateral bracing during alveolar stops that had previously not been identified in typical adult speakers (n=15). These detailed group studies provide important contributions to our continuing understanding of lingual palatal activity during speech production. However, often the adult data is from similar groups of researchers (e.g. Gibbon and colleagues, or McLeod and colleagues) and, as can be viewed above, present small numbers of participants. While typical articulation data is not limited to adult speakers, adults are much better presented than children in the literature.

Considering the slightly invasive process of obtaining an EPG palate (and the limited life span it may have with those still growing), it is perhaps not surprising that studies of lingual articulation patterns in typical children are less common than those with adults. An early investigation of a sole group of typical children performed by Fletcher (1989) presented lingual articulatory information on affricates and sibilants from nine 6-14 year olds, to investigate articulation developments throughout childhood. Fletcher's findings indicate a lessening of lingual palatal contact in consonant articulation across the ages. However, often normative data is provided by clinical studies that recruit typical children as controls and these controls appear in more than one study. For example, Gibbon, Hardcastle and Dent, (1995) present data from one 12 year old children (this same one appears in Hardcastle, Gibbon & Scobbie, 1995); Hardcastle and Morgan, (1982) present data from two typical children, although not clearly stated, between the ages of 6 and 13 years and Hardcastle, Morgan-Barry and Clark (1987) assessed a group of 4 children between the ages of 7 and 9 years. Lee, Gibbon and O'Donovan (2013) provided 8 typical children as a control group for a study of speech sound disorders. The typical controls from this were the same ones included in Gibbon (1999) and Lee, Gibbon, Crampin, Yuen, & McLennan (2007), aged 4-10 years. For control group cohorts, Dagenais and Critz-Crosby (1991) recruited a larger than typical number of control participants in their EPG study of lingual-palatal consonant production in children with hearing impairment. They presented repetitions of CV syllables (C= /t,d,k,g,s,z,ʃ/ V= /i, ɑ/) from 10 typically developing children within a small age range (12;0-12;10). The study identified similar patterns across speakers for lingual palatal contact for all target sounds. Of these few studies, the accepted finding is that children present with articulatory patterns similar to those of adults (Hardcastle, 1987). As children are noted to present with signs of motor stabilisation as they mature and that acoustic studies have identified different spectral patterns for child and adult speech production, it may seem odd that there are no identifiable differences. It is suggested that the small groups and/or age ranges limits the generalizability of these findings. A further limitation to the presentation of typical data in this way is that results are often presented as a group mean, rather than investigating age-related characteristics of TD articulation (e.g. Lee et al., 2013). The lack of specific data on typical articulatory patterns may have been the motivation for Cheng et al. (2007) to present a large comprehensive study on EPG characteristics of consonant production in typical children (6-17 years) and adults. Cheng et al. (2007) is the largest study to date on typical consonant articulations from children, adolescents and adults. Information was recorded from a total of 48 speakers, producing /t/, /l/, /s/ and /k/ from aged 6yrs to adults. Cheng et al. (2007) identified overall similar patterns of articulation for all sounds across all speakers but there were small differences. For example, the younger children produced /t/ and /l/ with greater lingual-palatal contact than older children and adults. Their investigations of /s/ production confirmed the presence of a narrow groove and mean EPG frames show evidence of fronting of this groove with maturation. In contrast to what may be expected, they found no age differences for variability of articulation except in /k/ production where the younger children were significantly different (more variable) to the older children and adults. Based on these findings, Cheng et al. (2007) dispute early claims that children present with similar articulation patterns to adults (with their findings reflecting well established views of speech motor development).

Cheng et al. (2007) provides a detailed look at the development and progress of spatial articulation behaviour in children compared with adults but no study to date provides specific information from typical children younger than 6 years old. Lee et al. (2013) included young children in their typical control group but provided no individual information on these participants. Investigating younger typical speakers is important in developing a clear understanding of the variety of articulatory patterns (e.g. covert contrasts) expected in normal consonant acquisition.

2.5.3.1 EPG and sibilant analysis

Of the typical EPG studies to date, a high number of these have investigated lingual palatal patterns in sibilant production. Findings agree that the anterior lingual-palatal sibilants are produced with a narrow groove at the relative place of articulation for both children and adults (Cheng et al., 2007; Dagenais & Critz-Crosby, 1991; Dagenais et al., 1994; Fletcher & Newman, 1991; Gibbon & Hardcastle, 1987; Hamlet, Bunnell & Struntz, 1986; Hardcastle & Edwards, 1992; Hoole, Zeigler, Hartmann & Hardcastle, 1989; Liker & Gibbon, 2011; Pouplier, Hoole & Scobbie, 2010; Stone & Lundberg, 1996; Tabain, 2001; Wolf, Fletcher, McCutcheon, & Hasegawa, 1976) and EPG is considered one of the best ways to provide information on the nature (width and length) of the sibilant groove (Lindblad & Lundqvist, 1994). Many EPG studies of sibilant production analyse the articulation of the voiceless alveolar sibilant /s/, however only a small amount of research has assessed typical articulation patterns in /ʃ/ production (Dagenais et al., 2004; Dixit & Hoffman, 2004; Guzik & Harrington, 2007; Holst, Warren & Nolan, 1995; Liker & Gibbon, 2011; McLeod & Singh, 2009; Pouplier, Hoole & Scobbie, 2010; Sanders, 2007; Stone & Lundberg, 1996; Tabain, 2001) and a smaller amount assessing typical patterns of /ʃ/ in children (Shannon, 2001, in Gibbon, 2004). These studies, along with those reporting on typical /ʃ/ production in other languages (Catalan: Recasens & Espinosa, 2007; German: Fuchs & Koenig, 2009; Norwegian: Simonsen & Moen, 2004) support general findings of the presence of a narrow groove at the post-alveolar region (though see Figure 2-5 for between-speaker variability of this placement).

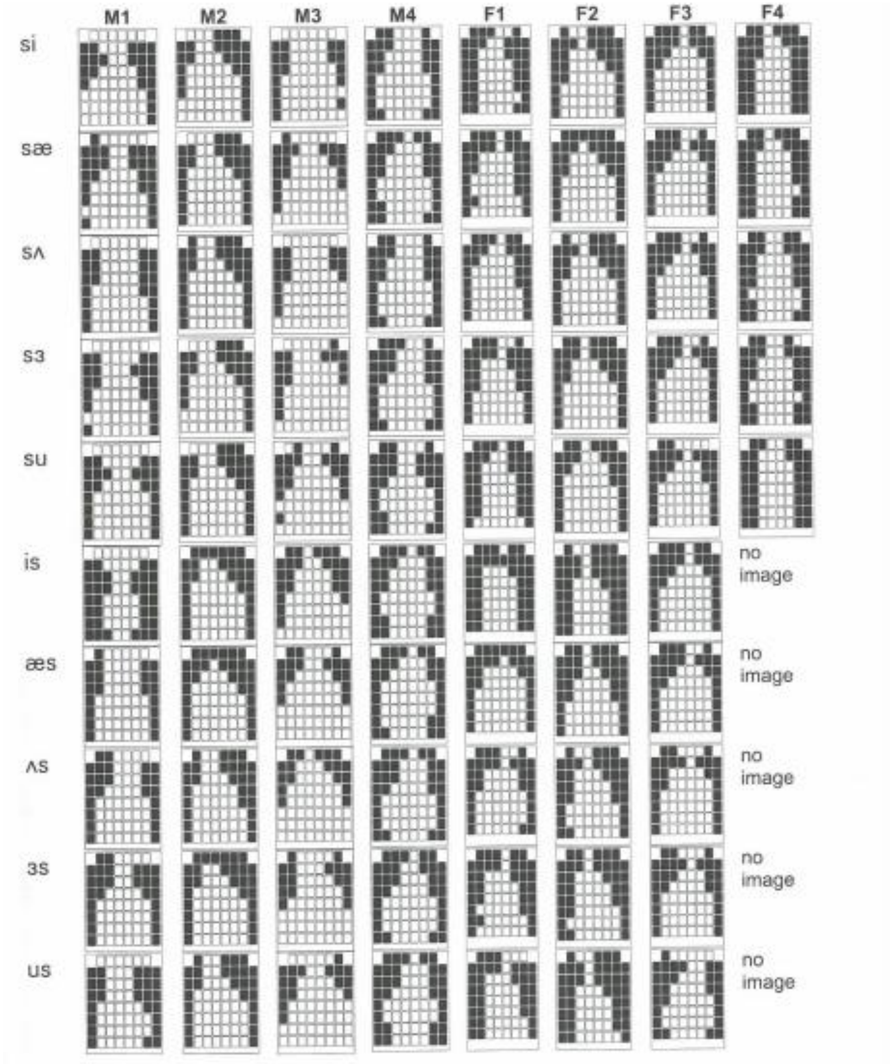


Figure 2-4: Between- and within-speaker variability in the maximum EPG contact frame for the production of /s/ by eight typical English-speaking adults. From "/s/" ***Speech Sounds: A Pictorial Guide to Typical and Atypical Speech*** **(p. 165) by Sharynne McLeod and Sadanand Singh. Copyright ©2009 Plural Publishing, Inc. All rights reserved. Used with permission.**

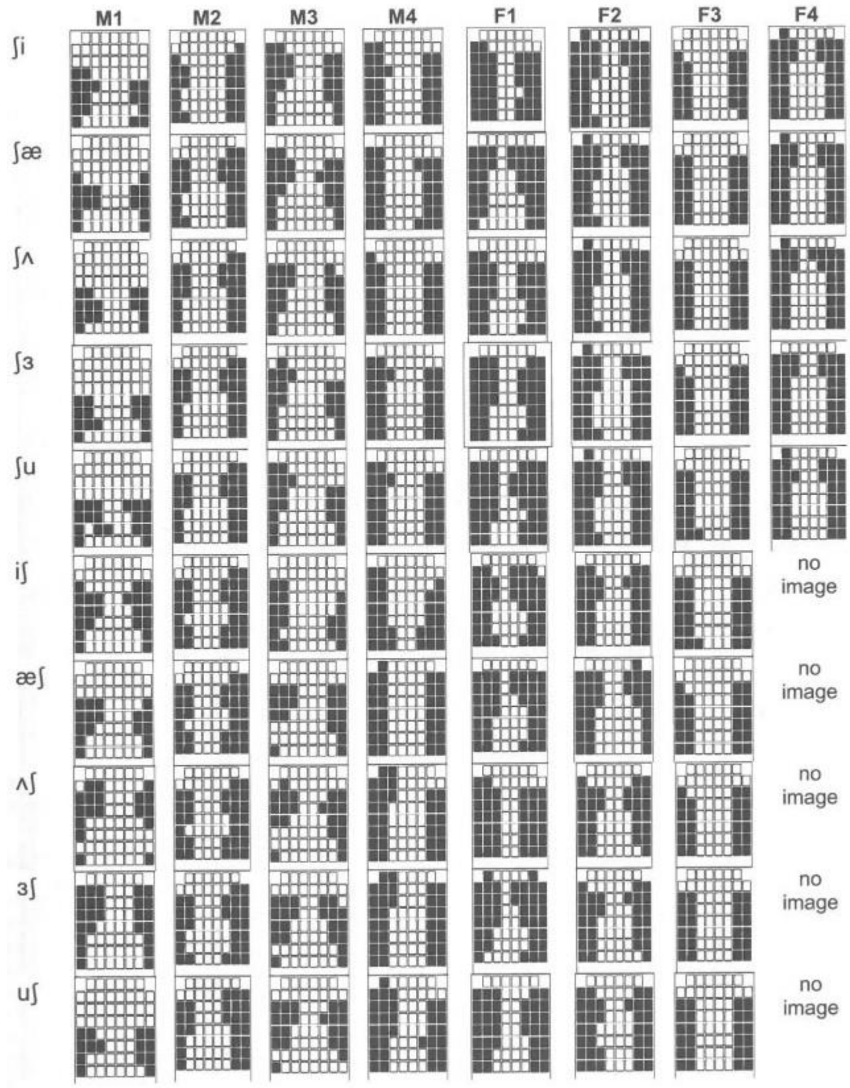


Figure 2-5: Between- and within-speaker variability in the maximum EPG contact frame for the production of /ʃ/ by eight typical English-speaking adults. From "/ʃ/" ***Speech Sounds: A Pictorial Guide to Typical and Atypical Speech*** **(p. 165) by Sharynne McLeod and Sadanand Singh. Copyright ©2009 Plural Publishing, Inc. All rights reserved. Used with permission.**

2.5.3.1.1 Groove Width

EPG analysis allows the researcher to investigate not just tongue placement on the palate but, in the case of the sibilant fricatives, the width and length of the tongue groove (but not the depth). This has led to studies investigating the nature of the central groove, particularly in the articulation of /s/, and at times, in comparison to the groove width and length in /ʃ/ (see Figure 2-4 and Figure 2-5 for differences between speakers for both sibilant groove widths). Studies present information regarding the actual measurements of the groove width (most often in millimetres:

Fletcher & Newman, 1991; Fuchs et al., 2007; Wolf et al., 1976) or discuss the number of electrodes untouched in the centre of the normalised palate.

While both the alveolar and post-alveolar sibilants are consistently described as being produced with a narrow groove, many EPG studies have found that the groove is wider for /ʃ/ than /s/ (Fletcher & Newman, 1991; Hoole, et al., 1989; Tabain, 2001). Ladefoged and Maddieson (1996) note that the groove width in production of the alveolar sibilant varies from 6 – 12 mm. In a more detailed study, Fletcher and Newman (1991) analysed groove width using EPG to determine the perceptual correlates of the sibilants /s/ and /ʃ/. They initially analysed the width and placement of the narrow groove of /s/ and /ʃ/ from two adult speakers, finding that /s/ had a groove width between 6-8mm and /ʃ/ had a groove width of 10-12mm. In a perceptual study of groove width in sibilant production, Wolf et al. (1976) measured /s/ production in 5 normal male speakers, in 4 different vowel environments. They ran a perceptual experiment with 14 listeners where the subjects had to identify a speech sound as: /s/, probably /s/, probably /ʃ/, or /ʃ/. The results from the experiment found that /s/ was identified when the groove was narrow (about 6mm) and near the rear edge of the alveolar region (14mm from tip to maxillary incisors). Segments produced with a 10-14mm groove were heard as /ʃ/ or /ʃ/-like when tongue contact was 10mm from the tip of the incisors. Groove width was also analysed in a study of voiceless and voiced alveolar sibilants in German (Fuchs et al., 2007). They suggest that the actual constriction size of the sibilant groove may be tiny as the electrodes on the EPG palate can be spaced very close together. They provide average measurements of 2.89mm for gaps between the electrodes in the first 2 anterior rows and 3.13mms between electrodes on the 3rd and 4th rows.

Similar to studies above, in their study on contextual effects on consonant production, Dagenais et al. (2004) note that the groove widths recorded for repeated productions of /s/ and /z/ in 10 American adults were narrower than those recorded for /ʃ/ and /ʒ/. Groove width for /s/ was noted to be between 4.5mm and 5.1mm compared to a range of 7.5mm to 9.6mm for /ʃ/ production. These are similar findings to the measurements taken from a group of typical children (Dagenais & Critz-Crosby, 1991) but groove width for /s/ was calculated to be 7mm, and /ʃ/ was 8.2-9.9mm depending on vowel context. There was no influence of the vowel on groove width for /s/, but a wider groove width was identified for /ʃɑ/ than /ʃi/. These findings suggest that children produce more similar constrictions for /s/ and /ʃ/ than adult speakers (though these studies do not take account of the differences in cavity size between adults and children).

The majority of studies, however, discuss groove width with regard to the number of electrodes untouched within the groove space (Cheng et al., 2007; Liker & Gibbon, 2011; McAuliffe et al., 2002; McLeod, Roberts & Sita, 2006). McLeod et al. (2006) found wide variation in EPG patterns of /s/ in a group of ten adult speakers, noting that the width of the narrow constriction can vary (ranging from 3 – 0 electrodes wide) and the narrow groove is occasionally asymmetrical (see also Hamlet et al., 1986), as illustrated in Figure 2-4 and Figure 2-5, from McLeod and Singh (2009). They also note that the absence of lateral bracing may be explained by contact with the teeth. However, this should be interpreted with the understanding that individuals' palate shapes differ, and electrodes on the palate may differ in spacing which will affect the interpretation of sibilant groove width and symmetry.

Cheng et al. (2007) show EPG composite frames from children at increasing ages for /s/ production. The average frames show a groove width of 3 electrodes for all ages presented (6 year to adult). Roberts et al. (2002) review /s/ productions from other studies of typical children (these include control subjects from Gibbon, 1999, and Hardcastle & Gibbon, 1997). Roberts et al. (2002) note that the groove width is variable (as is also noted in adults) and ranges from 1-2 electrodes in the examples they provide. The literature is lacking information on groove width measurements of children's productions of /ʃ/. To my knowledge, the only study providing this is Gibbon (2004) (citing Shannon, 2001) who presents a child with a groove width of 2-3 electrodes for /ʃ/ productions.

Whether analysing the actual palate measurements or the normalised palate, studies agree that /s/ and /ʃ/ are produced with a centralised groove. They are distinguished by a narrowing at the alveolar and post-alveolar place of articulation respectively but also by the width of the groove which is found to be wider for /ʃ/ than /s/. However, there are between- and within-speaker variations in groove length and width. In Figure 2-4 above, speaker M1 varies from a groove of 2 electrodes to 4 electrodes for target /s/, M2 and F2 both show patterns of complete alveolar closure as well as a narrow groove. Similar differences can be noted in Figure 2-5 with between-speaker groove placement and width variations for /ʃ/. It is expected that these levels of variability would be similar, or higher in typically developing children, but the existing accounts of sibilant articulation in this group are limited.

2.5.3.1.2 Articulatory variability in sibilant production

As noted in 2.4.6, sibilants are noted to be stable articulations, with high resistance to coarticulatory variation (Recasens, 1997), though some studies using acoustic and articulatory techniques have identified degrees of variation (Zharkova, 2011, 2012; Perkell, 2000). The presence of articulatory variation in sibilant production has been supported by typical EPG studies of English speakers (Fletcher & Newman, 1991; McAuliffe et al., 2002; Roberts et al., 2002; see also Figure 2-4 and Figure 2-5). McLeod et al (2006) present both between- and within-speaker variability for /s/ production in 10 adult speakers. However, other studies prefer to highlight the high levels of between-speaker variation (Roberts et al., 2002; Hiki & Itoh, 1986), in relation to low levels of within-speaker variation (Lindblad & Lundqvist, 1994; McAuliffe et al. 2002). Lindblad and Lundqvist (1994) suggest that between-speaker variability can be explained by the requirement of speakers with individual oral anatomy to produce tongue constrictions that achieve similar acoustic and perceptual results (as may be explained by motor equivalence, see 2.4.6.2 above) and that, in contrast, within-speaker variability is low as explained by the demands on the articulators to direct air precisely against the front teeth.

Evidence for either between- or within-speaker variation in children is lacking in EPG studies. As mentioned above, Roberts et al. (2002) present high levels of between-speaker variability for typical children, but with no information on within-speaker behaviour. It may be expected that EPG studies would identify higher levels of within-speaker variability in children in comparison to adults due to immature speech motor abilities, but little evidence exists comparing children and adults in this way. Shannon (2001, in Gibbon, 2004) looked at repetitions of word-initial /ʃ/ in a Scottish English child and adult and found higher levels of within-speaker variability for the child in comparison to the adult, and both presented with lower variability than a child with cleft palate. Timmins et al. (2009) also noted within-speaker variability for sibilant production in normal speakers. As McLeod et al. (2006) note, the levels of typical variability that are considered acceptable (or typical) are still yet to be established and require continued research.

2.5.4 EPG descriptions of error patterns

The articulatory information available from EPG analysis has been extremely useful in identifying abnormal articulation patterns in disordered speech populations. This is particularly noted in speakers with complex speech errors where even narrow auditory transcription has proven difficult. EPG can provide more detail, or support auditory phonetic analysis of complex speech errors. One such example is in cleft palate where EPG has been used widely (Gibbon, 2004; Gibbon & Crampin, 2001; Gibbon, Ellis & Crampin, 2004; Gibbon & Hardcastle, 1989; Howard, 1993; Yamashita, Michi, Imai, Suzuki & Yoshida, 1992) for both analysis and treatment, with studies finding evidence of disordered articulations and otherwise unidentified click productions, labial-lingual double articulations, and disordered sibilants (Stokes, Whitehill, Yuen & Tsui, 1996). Other studies have focussed on articulation and phonological speech disorders (Gibbon et al, 1990; Gibbon et al., 1996; Gibbon, 2002; Gibbon & Hardcastle, 1987; Hardcastle, 1987; Hardcastle et al., 1995; Howard, 2004), motor speech disorders such as dysarthria, Parkinson's disease, Apraxia of Speech (Bartle-Meyer et al., 2008; Edwards & Miller, 1989; Goozee, Murdoch & Theodoros, 2003; Hardcastle, 1987; Hardcastle & Edwards, 1992; Hardcastle & Gibbon, 1997; Hartinger, Tripoliti, Hardcastle & Limousin, 2011; Howard & Varley, 1995; McAuliffe & Ward, 2006; McAuliffe, Ward & Murdoch, 2006 & 2007; Nordberg, Carlsson & Lohmander, 2010; Southwood, Dagenais, Sutphin & Mertz, 1997; Sugishita et al., 1987; Wood & Hardcastle, 2000) and Aphasia (Wood 1997). A comprehensive list of EPG studies is provided by Gibbon (2013).

2.5.4.1 Spatial distortions

Analysis using EPG allows for the identification of perceptually unclassified articulations in disordered speech production. Error patterns defined by Hardcastle and Gibbon (1997) as serial ordering abnormalities include misdirected articulatory gestures (Hardcastle & Edwards, 1992) and articulatory drift. Misdirected Articulatory Gestures (MAGs) have been reported on in various studies of acquired speech disorders (Hardcastle et al., 1985; Hardcastle & Edwards, 1991; Wood, 1997; Wood, Hardcastle & Gibbon, 2011). These articulations are dynamic errors where the speaker initially attempts an incorrect placement of the tongue but then produces the correct articulation (e.g. a velar constriction for target /t/, supplemented eventually by an alveolar constriction, creating a double articulation pattern). Double articulation patterns are perceptually hard to identify but the EPG analysis technique can successfully illustrate the nature of these patterns, even if the listener cannot. Gibbon and Crampin (2001) assessed the amount of lingual contact present in 27 speakers with cleft palate during the production of the English bilabial consonants (/p/, /b/, /m/). Their study investigated the amount of lingual-labial double articulation present, finding that 11% of their speakers produced lingual contact during the production of bilabials. A common feature of disordered articulation, double articulations may suggest that speakers experience an error in phoneme selection during planning stages of articulation (Hardcastle et al., 1985).

Another common spatial distortion is increased lingual-palatal contact. This has been identified in the articulation patterns of many different clinical populations. A particular error pattern of increased contact was identified by Gibbon (1999) as an undifferentiated gesture (UG). UG is a term suggested by Gibbon (1999) to represent articulations that involve simultaneous tongue-palate contact in the anterior and posterior regions. These patterns show a large amount of tongue contact with the palate, leading Gibbon (1999) to suggest that they are a result of the lack of distinct control of the tongue tip and tongue body. These patterns are different to MAGs as they involve whole tongue gestures. Undifferentiated gestures have been noted in many different EPG studies (speech sound disorders: Dagenais et al, 1994; Gibbon 1999, cleft palate: Gibbon. 2004; Yamashita et al, 1992) and often identified for perceptually acceptable alveolar stop productions (Gibbon et al., 1995; Lee et al., 2013). From the 10 children with speech sound disorders (SSD) studied by Gibbon et al. (1995) one of these showed undifferentiated gestures for acceptable alveolar stop production. Additionally, Lee et al. (2013) found significantly higher levels of lingual palatal contact for perceptually acceptable tokens of alveolar stops in children with SSDs compared to a group of TD children.

Identification of spatial distortions has provided evidence for covert contrasts within typical and disordered speech populations. Hewlett (1988) identified covert contrasts as a measureable distinction between two sounds which is unidentified by auditory analysis. As such, these differences are identified through instrumental analysis techniques such as spectral analysis and EPG (Li et al, 2009; Scobbie, Gibbon, Hardcastle & Fletcher, 2000). Acoustic and EPG studies have indicated presence of covert contrasts in manner, place and voicing features (Li et al., 2009; Munson, Edwards, Schellinger, Beckman & Meyer, 2010; Scobbie, 1998), in fricatives and stop productions. Information gained from EPG analyses is one of the few ways that covert contrasts have been identified in both typical and disordered speech populations (Gibbon & Crampin, 2001).

2.5.4.2 Spatial and temporal variability

EPG provides a quantitative spatial variability index, which can identify within-speaker articulation variability across repeated productions of speech. EPG studies have identified both spatial and temporal variability in groups of speakers with Apraxia of Speech (Hardcastle & Edwards, 1992), Down's syndrome (Timmins et al., 2007), and cleft palate (Hardcastle et al. 1989), reflecting immature or disordered speech motor abilities.

2.5.4.3 EPG analysis of sibilants in disordered speech populations

EPG analysis is particularly suited to investigations of sibilant production. As established above, sibilants involve central airflow directed through a narrowed groove. The lingual-palatal information presented via EPG provides measureable data regarding the nature of this particular articulation pattern. Instrumental analysis of sibilant errors has identified the most common as: fronted to produce dental articulations of /s/ (ranging from interdental [s], [θ] to [s̪]), produced with lateral airflow, or retracted (Gibbon & Hardcastle, 1987). Gibbon and Hardcastle (1987; 204) note that the lateral misarticulation is "notoriously resistant to conventional therapy", which has led many clinical researchers to employ EPG to aid in the description and intervention of lateral misarticulations of /s/. The majority of the literature concerning EPG and sibilants in disordered speech populations reflects this wide interest. Earlier Japanese studies of sibilant production using EPG with cleft palate noted that errors are typically one of three types: Lateral misarticulation, palatalised misarticulation and nasopharyngeal misarticulation (Hardcastle & Edwards, 1992; Yamashita, Michi, Imai, Suzuki & Yoshida, 1992). Hardcastle and Edwards (1992) also identify these three types of errors in children with CAS but suggest a 4th type of error, pharyngeal misarticulation (also identified for target /s/ production in cleft palate, Howard (2004)).

Analysis of sibilant production using EPG has been continuous since the earliest EPG studies. These studies have presented evidence of many different spatial distortions for the alveolar sibilant (with less information on /ʃ/) (Gibbon & Hardcastle, 1987). Hardcastle et al. (1989) assessed sibilant articulation (alongside a variety of other consonant sounds) in 2 speakers with cleft palate and noted lack of grooving and complete contact across the palate (transcribed as lateral). Similarly, Hardcastle, Morgan-Barry and Nunn (1989) analysed sibilant production in 2 children with cleft palate who produced articulatory patterns with no evidence of a narrow groove, and were suggested to be similar to a lateral fricative pattern identified by Yamashita, Michi, Imai, Suzuki and Yoshida (1992).

Palatal and lateral misarticulations of /s/ are presented in Hardcastle et al. (1991) in speakers with persistent speech difficulties. The palatal realisations all show posterior palatal contact, with lateral bracing up towards the alveolar region (similar to those identified in Yamashita et al., 1992). Perceptually, lateralisation is a common error identified in EPG studies of lingual fricatives. The lateral misarticulations identified in Hardcastle et al. (1991) are not consistent across speakers; varied patterns are presented e.g. a narrow groove, complete anterior contact and almost complete palate contact. These categories are initially defined by perceptual analysis of the sound and then the EPG pattern is analysed which may account for the variability in the lateral misarticulation pattern, and, as noted by the authors the patterns presented do not take into account individual palate differences. These findings are noted elsewhere, with Yamashita et al. (1992) concluding that there are many different lingual-palatal patterns created for the same perceived misarticulations. Additionally, Howard (1995) presents different EPG patterns for lateral misarticulations, and further others in Howard (2004). Work by Dagenais, Critz-Crosby and Adams (1994), studying lateral lisps, also identify differing patterns of articulations for similar perceptual errors (in this case lateralisation of /s/). Their data found lateral sibilants produced with different articulatory configurations in each speaker (in one speaker lateralisation was produced with complete alveolar contact, in the other a midline groove was produced). Gibbon et al. (1995) analysed 10 children with production difficulties of /s/ and /ʃ/ using EPG. They found a range of difficulties, particularly lateral fricative production but also undifferentiated gestures (see section 2.5.4.1), a category that encompasses a range of articulations which have increased lingual contact (examples of these can be seen in Chapter 4 and 7).

Similar findings have been identified in speakers with dysarthria and apraxia of speech. In their study of adults with dysarthria, Hardcastle, Morgan Barry and Clark (1985) found complete closure and lack of grooving for word initial productions of /ʃ/. They also found evidence of high levels of within-speaker spatial variability and retracted groove patterns. Additionally, Kuruvilla, Murdoch and Goozee (2008) found increased lingual-palatal contact for sibilant and plosive production in speakers with dysarthria. Hardcastle and Edwards (1992) analysed sibilant production in adults with AOS and identified errors in /s/ and /ʃ/ production. These involved retraction of /ʃ/, palatalization of both /s/ and /ʃ/.

To summarise the increasing amount of sibilant investigation via EPG, Roberts, McLeod and Sita (2002) collated information on impaired and normal alveolar sibilant productions from EPG studies (including those mentioned above) and identified the following features of disordered sibilant articulations: higher overall amount of tongue-palate contact, higher amount of contacts on the palatal region, lateral gaps or fewer tongue-palate contacts in comparison to the normal. The presence of these particular articulation errors have been linked with abnormal motor abilities or sensory feedback difficulties (Dagenais et al., 1994).

2.5.4.4 EPG analysis of speech in Down’s syndrome

As mentioned earlier there are a few studies that have assessed the speech patterns of children with DS using EPG. The first couple of studies to emerge in DS were Hamilton (1993) and Gibbon et al. (2003). Subsequent studies using EPG with DS (either for descriptive or intervention purposes) have arisen from a subset of the same data in this PhD (Cleland et al., 2010; Cleland, Timmins, Wood, Hardcastle & Wishart, 2009; McCann & Wrench, 1997; Timmins, Cleland, Rodger, Wishart, Wood & Hardcastle, 2009; Timmins, Cleland, Wood, Hardcastle & Wishart, 2009; Timmins et al., 2007; Timmins, Hardcastle, McCann, Wood & Wishart, 2008; Timmins, Hardcastle, Wood & Cleland, 2011; Wood, 2010; Wood, Wishart, Hardcastle, Cleland & Timmins, 2009).

In her study, Hamilton (1993) analysed the speech production of three young adults with DS (17, 17 and 20 years old). She analysed tongue contact patterns for alveolar stops /t, d, n/ and /l/ and found more palatal and velar contact for these target sounds than in a sole control speaker. For velar stops /k, g, ŋ/, she noted decreased contact across the velar region for 2 of the 3 speakers with DS and increased palatal contact for /s/. She suggests that this increased tongue contact is possibly due to the size of the tongue in relation to a small oral cavity, which is supported by studies into palate shape and size in DS (see section 2.2.2.1). However, Hamilton's findings are based on a comparison with a single control speaker who uses standard productions. This ignores the a range of possible typical articulations that could produce acceptable productions of these target sounds, including increased contact for alveolar stops and decreased contact for velar stops (this is a related to the size of the EPG palate as it may not extend back to the velar place of articulation in all speakers). While this study provides a very detailed look at speech production in a small group of speakers, it is limited in its use of a small group of young adults with DS and the use of only one control speaker. Gibbon et al. (2003) also identified increased lingual palatal contact in a 10 year old child with DS. This was an intervention study which identified and remedied velar fronting via 12 EPG sessions. Wood et al. (2009) reported on pre- and post-therapy measures of two case studies of young people with DS. One child had problems with the production of target /s/ (the other target /k/) both children showed signs of perceptual and articulatory improvement after 12 EPG intervention sessions. Timmins et al. (2009) analysed the production of /ʃ/ in a much larger group of children with DS (20 participants from the same dataset as reported in this PhD study) and 2 control groups (8 cognitively matched typically developing children and 8 adults). EPG was used to measure variability and patterns of lingual contact. The DS group showed high levels of incorrect productions and used substitutions not found in the TD group. Timmins et al. (2011) presented information on the production of target /t/ from, again, the same speakers involved in this PhD study. The EPG analysis produced a range of articulation patterns that were not typically found in the production of /t/. This applied to both the errors and the tokens considered perceptually correct. These findings suggest that articulation errors in children with DS do not follow a typically delayed pattern.

These studies (Hamilton, 1993; Gibbon et al, 2003; Timmins et al, 2007, 2009, 2011; Wood, 2010) all contributed and built on important phonetic information in our understanding of speech production in DS but they are either based on case studies (Hamilton, 1993; Gibbon et al., 2003; Wood, 2010), small groups (Timmins et al., 2007) or on one particular consonant (Timmins et al., 2009; Timmins et al., 2011). There is clearly a need for a larger scale in-depth analysis of speech articulation patterns in DS using articulatory analysis techniques such as EPG.

2.5.5 EPG as an intervention technique

EPG has also proven to be an increasingly useful tool in speech and language therapy intervention. EPG can reveal underlying patterns in articulation that enables investigation beyond the auditory analysis. It can provide a more objective source of articulatory errors, which can be assessed pre- and post-intervention to measure efficacy of treatment. Finally, EPG can be utilised in intervention as a visual feedback tool. In this particular area, EPG has been successful in the remediation of speech difficulties in a range of speech and language clients, often with intractable speech errors (resistant to traditional therapy approaches). However much the area has grown, evidence of gains is still limited to single cases or small group studies (Gibbon, 2010). The lack of large intervention studies with EPG is exemplified by the Cochrane review performed by Lee, Laws and Gibbon (2009) regarding the use of EPG as an intervention techniques for articulation errors in speakers with cleft palate. In this review the authors identify a large number of EPG intervention studies for cleft palate but most of these employed small scale designs. Although the majority of these studies agree that EPG is a useful intervention technique, the final number of studies meeting their criteria was limited to one study (Michi et al. 1991). The authors conclude that there is a requirement for a randomised control trial for EPG intervention in the future. Although large scale trials are lacking, small scale intervention studies identify high success rates, particularly with the remediation of persistent speech errors (Dagenais et al., 1994; Gibbon and Hardcastle, 2004).

EPG has been applied as an intervention technique for children with DS in a few publications (Cleland, Timmins, Wood, Hardcastle & Wishart, 2009; Gibbon et al., 2003; Wood et al, 2008). Two of these studies were based on the same intervention process and data (Cleland et al., 2009; Wood et al., 2009). Cleland et al. (2009) presented pre- and post-intervention EPG data from 6 children with DS (5 of who had intervention for sibilant errors), and Wood et al., (2008) presented similar data from two children. Supporting Gibbon et al. (2003), both Cleland et al. (2009) and Wood et al. (2009) found that children with DS can show articulation improvement with EPG intervention, but only if errors are mainly lingual-palatal.

2.5.6 Summary: Electropalatography

In summary, although EPG is limited to analysis of lingual palatal articulation, it is well-suited to investigation of /s/ and /ʃ/ production. The frequent use of EPG in disordered speech populations has identified articulatory patterns for /s/ and /ʃ/ that are otherwise unidentified through auditory investigations (Gibbon et al., 1996). EPG provides a recording and analysis technique that presents detailed quantitative measures (variability, temporal and spatial measures) and descriptive data. Hardcastle and Gibbon (1997; 166) note that EPG error patterns present within the following areas: “spatial distortions, temporal and serial ordering abnormalities, and errors of substitution and omissions”. These perceptually unidentified articulatory patterns can provide information on the production and planning stages of speech articulation, with some spatial errors providing information on speech motor deficits that would be otherwise unidentified. Importantly, EPG provides an objective measure of investigation of sibilant articulation.

2.6 Summary of chapter

Children with DS present with a behavioural phenotype that includes low intellectual ability, anatomical and structural differences, hearing loss (Balkany et al. 1979) and communication difficulties (Roberts et al. 2005). The speech and language difficulties experienced in this group have been found to be mostly a lack of expressive language. These difficulties have been found not to correlate with cognitive age so this leads researchers (Cleland et al, 2010) to suggest that problems are related to a combination of differences with motor ability, hearing loss, palate size and dentition. Of particular interest in this study is the investigation, and impact of speech motor control difficulties in this population.

As discussed above (section 2.3.1) early studies of speech articulation in children with DS have interpreted errors as reflecting a delayed phonological disorder. However, some of these studies have identified presence of atypical distortions (commonly considered to suggest a phonetic disorder). The presence of these errors, and the small amount of data from instrumental analyses of speech in children with DS, may provide support for the suggestion of speech motor difficulties in this group. However (as noted in 2.2.5.3) evidence from speech data to support these difficulties are still lacking.

Sibilant fricative sounds are proposed as a suitable dataset for the further investigation of error types and speech motor difficulties in children with DS. As commonly misarticulated speech sounds, a high level of error production will hopefully provide a large amount of data for analysis. Establishing the nature of these errors can supplement previous studies into speech production in DS but may also provide evidence of unidentified error patterns. It is proposed that an ideal way of investigating these error patterns is by using imaging techniques such as EPG. The use of EPG has provided measurable gains in speech disorder research as it can provide simple representation of lingual palatal contact which can be analysed by various measures. It is particularly suited to the analysis of sibilant production, due to the representation of the coronal plane (therefore the imaging of the central grooved articulation). The investigation of sibilant production can be assisted by a variety of measurements, including spatial variability, precise tongue placement and amount of tongue contact. It is proposed that these quantitative measures will provide greater insight to the articulatory nature of sibilant errors in these children with DS, and will also provide an objective measure of articulatory aspects of speech motor control, particularly spatial accuracy, and consistency of articulatory movement (Fletcher, 1992).

The high evidence of errors, in addition to the typical stability involved in the articulation of these consonants, associated with sibilant production in this population, and the detailed level of analysis gained by EPG led to the following research aims and hypotheses.

2.7 Research Aims and hypotheses

The main motivation for this thesis was to further investigate the nature of articulation errors in children with DS. Previous research (e.g. Timmins et al., 2009) has queried the presence of a delayed speech disorder in this population as evidence exists to contradict this suggestion. As such, the nature of the speech disorder in children with DS is still unknown. It was further considered that if atypical errors are evident in this population, does this suggest that speech motor disorders are the main obstruction to successful speech production in children with DS? In order to answer this more detailed articulatory information is required. This study was derived from a large project with the aim of investigating speech motor abilities in children with DS using EPG. This particular PhD study was motivated by the high levels of errors in sibilant production in this population, and an interest into whether articulatory evidence from EPG measurements and visual analysis of these errors could support a claim that speech motor abilities are impaired, and as such, have an impact on perceptual acceptability in these speakers. The following research questions and hypotheses were proposed:

RQ1 – Do children with DS show more atypical articulation patterns in errors of sibilant production in comparison to TD and typical AD?

Method: Perceptual analysis of sibilant production (DS, TD and AD groups)

Hypotheses:

- H1: As a group selected on the basis of experience difficulty with speech production, it was expected that the DS group would show significantly less overall perceptual acceptability (PTA) than the TD and AD group. This is consistently noted in studies of children with DS (e.g. Roberts et al. 2007).

- H2: The DS group would show no relationship between PTA scores and chronological age (as noted in Cleland et al., 2010), unlike the TD group who would show a significant relationship with PTA increasing with age.
- H3: The DS group would show more atypical patterns of errors (as noted from Phonetic error (PE) scores and Error pattern analysis) (as found in e.g. Dodd, 1976), than the TD and AD group.

Method: Quantitative and descriptive EPG measures of sibilant production (DS, TD and AD groups)

Hypotheses:

- H4: Reflecting the high amount of errors expected in production of target sibilants, it is hypothesised that the DS group will present with significantly decreased space between Centre of gravity (COG) measures for /s/ and /ʃ/ compared to the TD and AD groups for all tokens, and the perceptually acceptable tokens.
- H5: The DS group will show significantly higher levels of lingual-palatal contact (as shown from Whole total contact (WTM) scores) in the articulation of voiceless sibilants compared to the TD and AD groups (as noted in Hamilton, 1993).
- H6: Speakers with DS would show increased presence of atypical EPG patterns for all target sound productions compared to TD and AD group. The TD group would present with mostly typical EPG patterns.
- H7: The DS group will show a wider spread 2D pattern of canonical analysis than the TD speakers, less similar to the AD testing group

RQ2 – Is there evidence of speech motor difficulties in children with DS as measured by spatial and temporal variability?

Method: Quantitative EPG measures of sibilant production (DS, TD and AD groups)

Hypotheses:

- H8: The COG and WTM scores will show higher levels of within-speaker variability (measured by a coefficient of variation) in the DS group compared to the TD and AD groups.
- H9: EPG spatial variability analysis will reveal significantly higher levels of within-speaker variability (OSVar & PSVar) in the production of voiceless sibilants in the participants with DS compared to the TD and AD groups and this will show no relationship to age (as would be expected in the TD group).
- H10: Dynamic EPG measures will show higher levels of variability for the five case study participants in comparison to TD and AD mean
- H11: The DS group will show significantly longer (or indeed shorter) durations of the target sounds than the TD and AD groups. Temporal variability (as measured by a COV of duration) scores will reveal higher levels of within-speaker variability for the DS group compared to the TD and AD group.

Method: Diadochokinetic tasks (DS and TD groups)

Hypotheses:

- H12: DDK tasks would show slower rates and lower levels of accuracy in the five case study participants in comparison to the TD group to reflect speech motor difficulties in DS.

RQ3- Do children with DS present with atypical EPG measures and patterns for perceptually acceptable productions of sibilants?

Method: Quantitative and descriptive EPG analysis (DS, TD and AD groups)

Hypotheses:

- H13: Speakers with DS will present with different quantitative EPG measures (COG & WTM) for perceptually acceptable tokens of sibilants compared to TD and AD speakers.
- H14: Speakers with DS will present with atypical articulation patterns for perceptually acceptable tokens which will not be shown in the TD or AD speakers

3 Methodology Part One

3.1 Introduction

This study aims to look at the production of sibilants in young people with Down's syndrome (DS) using two phonetic analysis approaches: auditory and articulatory analysis. Although not exhaustive, utilising two analysis techniques should help provide a clear picture of sibilant production in this population

This study will provide results from three analysis approaches:

1. Perceptual and Electropalatographic (EPG) quantitative measure of articulation in children with Down's syndrome compared to typically developing (TD) children and adults (AD)
2. Descriptive EPG pattern analysis of articulation in children with Down's syndrome compared to typically developing children and adults
3. Case studies of articulation patterns in with Down's syndrome compared to typically developing children

3.2 PhD origins: MRC project

The PhD study originated from a 3 year MRC funded project: '*Assessment and Treatment of Impaired Speech Motor Control in Down's Syndrome'* (MRC grant number G0401388) at Queen Margaret University (QMU), Edinburgh, on which the PhD researcher was employed as a research fellow (2005-2010). The data collection, participant recruitment, and some of the data analysis included in this PhD study were initially completed for the purpose of this project. From this point onwards the original project will be referred to as 'The MRC project'.

The PhD researcher was employed as a Research Fellow on the above mentioned MRC Project: '*Assessment and Treatment of Impaired Speech Motor Control in Down's Syndrome'* (MRC grant number G0401388) at the Speech Science Research Centre in QMU. She was not involved in the initial planning of the project but for information, here are the aims put together by the original project team from the original grant proposal:

> "to identify characteristic speech motor patterns produced by DS children based on EPG and acoustic measurements, comparing these to patterns in TD speakers matched for cognitive status and/or stage in linguistic development (see below),
>
> 1. to evaluate the role of visual training with EPG in improving motor control relevant for speech production in DS children,
> 2. to determine whether improved speech motor control leads to increased intelligibility,
> 3. to evaluate whether variables linked to DS such as cognitive level, speech perception ability, chronological age, oropharyngeal and general motor development are good predictors of speech intelligibility,
> 4. to evaluate whether the variables above are good predictors of EPG intervention success.

The overarching aim of the project is to gain a greater understanding of the speech motor control deficiencies associated with DS and how these are likely to impact on speech development. The longer-term aim is to apply this knowledge therapeutically to develop speech production skills and thus to enhance quality of life." (MRC Grant Proposal G0401388)

The Research Fellow was employed to aid in recruitment, to arrange manufacturing and distribution of EPG palates, aid in recording of speech data and to analyse the speech data. The Research Fellow worked alongside a Speech and Language Therapist (SLT) who was also involved in recruitment but whose main task was the recording of speech and language data, and planning and providing speech therapy intervention.

As the project progressed the SLT focussed on development of therapy goals and delivery of intervention (as reflected in her subsequent publications, Cleland et al. (2009; 2010)). The PhD researcher, as research fellow, focussed on specific analysis of the speech production abilities of the DS and TD groups involved in the project (as reflected in her subsequent publications, Timmins et al. (2007; 2008; 2009; 2011)).

Many aspects of the following methodology were determined by the MRC investigation team prior to the PhD researcher's involvement on the project. Other decisions were made solely by the PhD researcher.

The MRC investigation team took the lead for decisions regarding:

1. The number of participants
2. Age range of participants (both the experimental and control groups)
3. Recording of speech data
4. The use of the EPG analysis technique

The PhD researcher took the following specific decisions primarily to address the research questions in this thesis:

1. Identifying sibilants to be analysed in detail
2. Recording typical adult data
3. Arranging additional transcribers for perceptual analysis
4. Additional EPG measurements (Whole total contact, Alveolar closure and Canonical analysis)
5. Creation of pattern taxonomies for three identified target sounds
6. Subsequent pattern analysis employing taxonomies
7. The decision to analyse all attempted productions of target sounds and the perceptually acceptable productions separately
8. Analysis of case studies to assess impact of structural, motoric and auditory differences on speech production

The majority of data analysis in this study was performed by the PhD Researcher (in the few cases where this does not happen, it will be highlighted who performed the analysis). Information is also available in Appendix I.

3.3 Recruitment of Participants

3.3.1 The MRC Project experimental group

Initially the MRC project aimed to record 30 children and young people with DS living in the central belt of Scotland. The initial contacts were made via a database held by the University of Edinburgh. The large database contained information about children who were participating or had participated in a research project at the University of Edinburgh (G0000325) at the time of recruitment and whose parents had indicated interest in participating in further studies. Other recruitment was achieved via flyers disseminated by Down's Syndrome Scotland to their members, and media articles in local newspapers and magazines. The children involved in the MRC study were required to attend Queen Margaret University for a series of recordings and therapy sessions (depending on subsequent therapy group allocation, either EPG therapy, articulation therapy or no therapy). During the course of recruitment a total of 55 young people were contacted. The number of those contacted who were later included in the project was 26. 14 of those contacted did not attend an initial meeting with the researchers due to parental concerns or travel problems. A further 14 were eliminated from the project for a wider range of reasons, these included: lower than desired cognitive score, no intelligible speech, participants' fear of the dentist, use of a pacemaker, no speech problems and travel issues. A final participant was removed from this study as the EPG recording provided ambiguous patterns that could not be interpreted confidently when matching with perceptual data (which throughout the recording session displayed very little lingual-palatal contact suggesting perhaps a recording error).

The participants were sent out an information pack with notes for the parents/carers and for the children. Each participant and parent/carer was invited to QMU to meet the MRC project team, see the equipment involved (EPG analysis hardware/software) and learn more about the project and tasks required. The parents/carers were either recruited on site or left to consider their child's recruitment in the project in their own time.

The final group of children with DS involved in the project and also this study were aged 8;3-18;9 years (mean 13;5, SD 3.11), and the group comprised of 14 boys and 11 girls. The wide age range was chosen to ensure a large participant group within the 3 year period of the MRC project. The children were all screened to identify potential obstacles to assessment:

- Cognitive ability had to be more than 3 years
- No severe hearing loss (aided threshold better than 40dB)

- No current emotional and behavioural difficulties
- No co-existing diagnosis of autism
- Not fitted with a pacemaker.

As the children were taking part in a large EPG intervention study they were required to present with errors involving lingual-palatal consonants. Severity of speech disorder was assessed using the phonology subtest of the Diagnostic Evaluation of Articulation and Phonology (DEAP, Dodd, Hua, Crosbie, & Holm, 2002) which provides a percentage consonants correct (PCC) score (Shriberg & Kwiatkowski, 1982). Oromotor function was assessed using the Robbins and Klee clinical assessment of oropharyngeal motor development in young children (RK, Robbins & Klee, 1987) and cognitive ability was assessed using the full form of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-IIIUK, Wechsler, 2003) (for more information on the results of these assessments see Cleland et al, 2010). The results of the DEAP and the WPPSI assessments helped decide whether a participant could remain in the study after the initial consultation (for example, a verbal age equivalent (VAE) over 3yrs and a DEAP score which was less than 100%). These assessments were completed by the SLT researcher involved in the project (DEAP and RK) and the WPPSI cognitive assessment was recorded and scored by a psychologist employed on the project. The final DS group participants are presented in Table 3-1 below.

The participants present with a wide range of scores for consonant production of the DEAP assessment (from 19% CC to 87% CC) which are overall lower than the vowel production scores from the DEAP (from 36%VC to 99%VC). The cognitive scores are low in this group and range from 3;11 to 5;9 for Verbal Age Equivalent (as measured from Verbal IQ in the WPPSI-IIIUK; Weschler, 2003). All participants from the MRC project were involved in this PhD study.

Participant	Gender	Age	Hearing	%CC	%VC	%RK Oral Function	VAE	PAE
DS01	F	11;7	Normal	67	95	79.81	4;8	6;4
DS02	M	16;6	Normal	33	66	51.92	5;10	<7;2
DS04	M	10;1	Normal	38	56	66.35	3;11	4;5
DS06	M	15;6	MCL	72	97	72.12	5;5	<5;11
DS07	M	10;11	BAHA	70	92	81.73	<5;1	<5;9
DS08	M	10;2	Aided	66	91	90.38	<4;0	>5;5
DS09	M	16;5	Normal	47	70	61.54	<4;1	<4;6
DS10	F	13;10	Normal	84	96	79.81	5;6	6;1
DS13	M	13;0	Normal	87	92	91.35	>6;3	>6;9
DS14	M	14;11	MCL	59	75	69.23	5;7	>7;2
DS15	M	18;9	Aided	81	96	81.73	5;3	<4;1
DS16	F	15;8	Aided	40	72	68.27	<4;1	<5;1
DS20	F	15;9	Normal	61	89	70.19	4;1	6;1
DS21	M	11;7	Normal	43	67	61.54	<4;1	>6;9
DS23	M	17;5	MCL	19	36	54.81	<4;1	>7;2
DS24	M	10;5	MCL	73	78	80.77	4;5	<5;8
DS25	M	16;3	Normal	54	75	66.35	<4;1	5;3
DS26	M	9;10	Normal	59	91	84.62	4;8	5;9
DS27	F	15;6	Normal	78	95	82.69	<4;10	>5;5
DS28	F	9;6	MCL	81	93	90.38	<4;1	<5;4
DS30	F	9;6	Normal	43	79	72.12	<4;1	5;1
DS34	F	9;2	Normal	82	99	79.81	5;9	5;10
DS36	F	8;3	Normal	63	86	63.46	<4;1	<4;3
DS37	F	13;1	Normal	74	87	81.73	5;0	6;3
DS38	F	15;9	Normal	83	96	85.58	4;8	>7;1

Table 3-1: Basic participant information: Experimental Group recruited for MRC project. BAHA: Bone Anchored Hearing Aid, MCL: Mild Conductive Loss, %CC: DEAP percentage consonants correct, %VC: DEAP percentage vowels correct, %RK Function: Percent score from Robbins-Klee Oral Function Test, VAE: Verbal Age Equivalent, PAE: Performance Age Equivalent

3.3.2 The MRC project control group

The control group consisted of 10 typically developing children from the Edinburgh vicinity. They were recruited via local media adverts, work-distributed emails and occasionally through the experimental participants. The initial target number was 15 children but this was lowered to 10 participants in total due to problems recruiting children young enough who were interested and comfortable in taking part in the project. The control group were aged between 3;8 and 7;1 years (mean: 6;1, SD: 1.0).

This age range was chosen in order to be closely matched to the DS group by cognitive age. The control group were also required to be measured for an EPG palate by an orthodontist and they were also asked to practice wearing the palate at home in preparation for their speech recording sessions at QMU (see 3.4.1 below for more details).

3.3.3 PhD study control groups

The PhD study used the same control group of typically developing children as the MRC project. The participant details are provided in Table 3-2 below.

Participant	Gender	Age	%CC	%VC	%RK Function	VAE	PAE
TD04	M	6;4	97	100	100	>7;2	>7;1
TD24	F	6;9	100	100	100	>7;2	>7;2
TD25	M	5;5	99	99	100	5;8	5;0
TD26	M	5;10	100	100	100	>7;2	>7;2
TD27	F	7;1	100	100	100	>7;2	>7;2
TD28	M	4;1	93	99	100	4;1	3;11
TD29	F	7;1	96	100	100	>7;2	>6;7
TD31	M	6;1	99	100	100	>7;2	>7;2
TD32	M	3;8	89	100	92	X	X
TD33	M	6;4	100	100	X	X	X

Table 3-2: **Basic Participant Information: Typically developing children from MRC project. BAHA: Bone Anchored Hearing Aid, MCL: Mild Conductive Loss, %CC: DEAP percentage consonants correct, %VC: DEAP percentage vowels correct, %RK Function: Percent score from Robbins-Klee Function, VAE: Verbal Age Equivalent, PAE: Performance Age Equivalent, X: Data not available**

The TD control group present with high scores for %CC and %VC (89%-100%) from the DEAP. The cognitive scores range from 3;11 to >7;2 (TD33 & TD32 did not complete a psychological assessment so no scores are available). The timing of the speech assessments was much later for TD28 than the cognitive assessments which should be taken into account when considering the relationship between the psychological and speech assessments in this group.

For the purpose of the PhD, eight typical adults with their own EPG palates were also recorded (this group were all staff at QMU and were all native speakers of

English spoken in the United Kingdom). The speakers ranged from 30-60 years old. There were 4 males and 4 females. All adults were experienced in recording speech using EPG. The adult speakers did not complete the speech and language assessments, only the speech data required for the PhD study.

3.3.4 Matching children with DS and control group

Initially the MRC grant application was written with the control group matching by chronological age but this was altered to cognitive age after feedback from reviewers. Some researchers have noted problems with cognitive-age control matching in the case of older children, particularly when investigating the nature of language development in this group. Van Borsel (1996) highlights that the cognitive ages of such control groups would be at a point where language development (in the case of articulation ability) has completed. Therefore typical articulation errors would not be available for direct comparison. The age range for the TD groups was a decision made by the MRC investigation team. This PhD study had a different concern regarding cognitive-matching. It was thought that in order to assess the impact of anatomy and structural differences on articulation ability, an age-matched control group would also have been beneficial. The financial limitations of this PhD meant that there were no resources available for further EPG data collection. Therefore the control groups for this thesis were limited to cognitively-matched children and a typical adult group.

3.3.5 Socioeconomic Status

No measures were taken to control for socio-economic status when recruiting participants.

3.3.6 Consent

Written consent covering audio and video recording and use of data for teaching and research was obtained from the parents/carers of the young people participating (see Appendix I) during the course of the MRC project. This extended to the use of the data for further analysis (such as in this PhD study).

3.3.7 Ethics

Ethical approval for the MRC funded project was acquired from the local NHS Trusts (LREC) and QMU Ethics committee.

3.4 Data collection

3.4.1 EPG palate acquisition

During the MRC Project all participants were provided with a custom-made EPG palate which requires a dental impression to be made and then a palate fitting session to be arranged. This stage of data collection could be time consuming and unpredictable. We used the same dental surgeon resident at two dental practices in Edinburgh city centre, trained in impression making required for EPG palates and the dental appointments were arranged by the PhD researcher. Once an agreed time was arranged the participants first attended for an initial impression. For some participants this process was mildly uncomfortable but there was a high success rate with both the experimental and control groups. Of the 27 final participants 9 found the dental impression to be an uncomfortable process. 1 of the 9 had two appointments in order to get the impression made but the others managed the process in one sitting.

The dental impression was set and trimmed at the dental surgery (this process took 2 weeks) and then collected by the PhD researcher. Once the dental impressions were set the individual impressions were sent to the EPG palate manufacturer Incidental. This process varied but could take a maximum of 4 months.

Another dental appointment was required to check that the EPG palate was suitable for the participant. Once the dental surgeon agreed that the EPG palate was a good fit, the children were requested to wear the palate for 2 hours prior to the recording session. It is well established that speakers require a period of desensitization to adjust to the presence of the EPG palate (McLeod & Searle, 2006). McAuliffe, Robb, and Murdoch (2007) suggest a period between 45 minutes and 3 hours is required in order to adapt to the EPG palate. The children in this study were asked to wear the palate for an increasing amount of time over a 2 week period prior to the recording. They were provided with feedback sheets to note how comfortable they felt during the allocated time for wearing the palate. The adult participants were asked to wear the palate for at least an hour prior to recording. As the adult participants were all members of the Speech Science Research facility at QMU, on the day of the recording, they were able to notify the PhD researcher when they felt that their speech had adapted to the palate.

3.4.2 Structural and dental information

During the dental impression, the Orthodontist completed a form which concerned aspects of the child's oral structure and dentition. This was only completed for some of the children as it was time-consuming for the Orthodontist and was considered by the Orthodontist to be misleading, containing incorrect descriptive categories. Information, when available was included in the case study analyses.

Palatal structural information was a desired measure but unfortunately the palates were kept by the participants after completion of intervention. A few years had passed between the participants' completion of the MRC project and the PhD Researcher's interest in measuring the palatal shapes of the speakers. The PhD researcher attempted to contact the parents/guardians of the participants, however many contact details were out of date or EPG palates and/or dental impressions had been lost. Of the 26 children with DS, 20 were contacted. From that 20, 4 palates were available to measure, therefore this measure was not pursued.

3.4.3 Speech data recording

All participants were recorded producing the speech data in the same clinic room at QMU on the same PC by the SLT employed on the MRC project (except the adults who were recorded by the PhD researcher). Auditory and articulatory data were recorded simultaneously using an Articulate Instruments Multichannel WinEPG™ system and the Articulate Assistant™ software (44.1 kHz sampling rate for the audio recording, 100fps for EPG frame capture) (Articulate Instruments Ltd, 2010). Although it has been established that live, or video recordings are important for detecting errors in /s/ production (Stephens & Daniloff, 1977), no video recordings were made of the participants during the speech data recording (see section 8.7.5.2 for a discussion of the impact of this).

The EPG recording technique requires the participant to wear their EPG palate which is then connected to a multiplexer that hangs around the user's neck. The multiplexer converts tongue-palate contact from the electrodes into digital signals for processing through the PC. The participants are then required to sit with constant contact with the hand grip in order to complete the EPG circuit. The items to be recorded were presented to the participant via the Articulate Assistant software both in word and pictorial form (see Figure 3-1) along with either <a> or <the> preceding, in order to ensure a neutral tongue-palate setting before production of the target consonant. This makes it easier for the researcher to correctly identify the onset of articulation for the target sound. However, the participants didn't always produce the determiners <a> or <the> which may reflect their overall poor language ability.

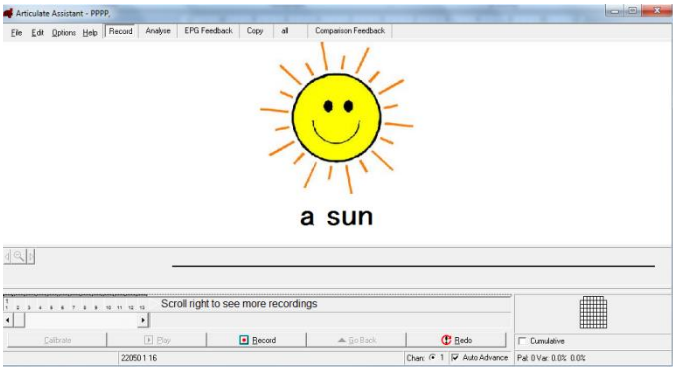


Figure 3-1: Example of prompt screen for 'a sun'

Each participant sat in front of the PC with the microphone to one side. The participant was asked to wait for a short beep before speaking in order to ensure the EPG contact was recorded. The SLT (and PhD researcher for AD recordings) was present for the data collection and could observe whether contact between the participant and the EPG circuit was broken (by viewing a feedback EPG frame on the computer during their recording). If this occurred the participant was asked to produce an extra token of the missed target word.

The PhD speech data was collected as part of many other speech and language measures. The participant was involved for up to an hour, and the data collection reported on in this study occurred in the middle of the session, generally taking about 5 minutes to complete. The speech data of interest for the PhD study was the same as the data collected for the MRC project, therefore no further data were collected.

Figure 3-2: Set up for collection speech data using WinEPG^{TM} system with Articulate Assistant software (image copyright: Dougie Barnett Photography)

The speech data selected for the PhD was a subset of the wordlist data collected for the MRC project. The speech sample recorded for the MRC project consisted of a wordlist (items and target sounds in Table 3-3 below) along with the DEAP assessment and sentence productions including the target words from the wordlist. The wordlist items analysed in this PhD are highlighted in the table. The wordlist was initially constructed to assess many aspects of speech sound production: coarticulation, multisyllabicity, assimilation, as well as the tongue-palate contacts used in the production of word-initial obstruents. The speech items were presented to the participant via the AA software. The wordlist was read through ten times in the same order, at a consistent speech rate during which acoustic and articulatory information was recorded.

Wordlist item	target sounds
a toe	WI /t/
a sun	WI /s/
a clock	WI /kl/ WF /k/
a sheep	WI /ʃ/
a chicken	WI /ʧ/ WM /k/ WF /n/
a red car	/dk/ coarticulation
the slippers	/sl/ cluster
a helicopter	multisyllabic word

Table 3-3: Wordlist recorded for MRC project

The data selected for the PhD was taken from the list presented in Table 3-3 above. The speech data included ten repetitions of target /s/ in ‘a sun’, and target /ʃ/ in ‘a sheep’. This is a small dataset but allows for a high level of detailed analysis in a large group of speakers.

The initial MRC project data collection design resulted in a wordlist that was not tailored to focus on sibilant production and therefore slightly limited in scope. For example, the sibilant sounds chosen for the PhD study only appear in one vowel context (for target /s/ it was /ʌ/, and for target /ʃ/ it was /i/). The impact of the following vowel on the sibilant articulation patterns is likely to be different for both target sounds. The high front vowel context of /i/ in ‘sheep’ will possibly result in a larger amount of dorsal-palatal contact than would be identified in a low vowel context (Proctor, Shadle & Iskarous, 2006). This dataset provides no instances of sibilants in word positions other than word initial: ‘the slippers’ was not included in this study as the word initial /s/ is in a consonant cluster environment and consonant clusters have been found to commonly be in error in children with DS. This limits the study to the analysis of word initial /s/ and /ʃ/ in the items ‘a sun’ and ‘a sheep’. Throughout the study the word initial obstruent /t/ in the item ‘a toe’ will also be analysed as a comparison item (chosen as it was suspected to be produced more successfully than the sibilants). Although limited by the previous decisions made for the MRC project, these two sibilant sounds are well-suited to EPG analysis and are also often disordered in this population and, although small, the dataset is simple and provides common lexical items produced 10 times in the same context.

The DEAP assessment also contained samples of sibilant production but there are few tokens (or appear as part of a consonant cluster) and were recorded as part of a longer speech activity (phonological assessment). These tokens were only analysed for the case studies (see below).

3.4.4 Additional Data for Case Studies

3.4.4.1 Speech data

To provide more information on articulation ability for the children analysed in Chapter 7, attempts at target /s/ and /ʃ/ were annotated and analysed from the DEAP assessment (the Articulation and Phonology tests). The DEAP was recorded (by the MRC SLT) while the child wore the EPG palate providing perceptual and instrumental data available for these tokens. For WI /s/ there was the possibility of the following tokens: *sock, scissors, sausage* (/s/-clusters were not included for analysis). The DEAP also provided some tokens of the target /s/ in WF position: *house, lighthouse.* For WI /ʃ/: *sheep (x2),* WF /ʃ/: *splash, fish, toothbrush,* and WM /ʃ/: *fishing* were possible tokens for analysis. The children did not always produce these words.

3.4.4.2 Speech motor measures

In order to establish a relationship between the articulatory problems apparent in this group and speech motor difficulties, DDK measures taken for the MRC study were presented for the case study participants. The DDK analysis protocol (McCann & Wrench, 2007) was applied to all speakers and they were recorded producing /pə/, /tə/, /kə/, /təkə/, and /pətəkə/. In this version of the DDK task, speakers produce the DDK tasks at various set speeds (following the SLT and/or a metronome). Both the DDK recording and the analysis of the DS group was performed by the MRC Project SLT. The TD data was analysed by the PhD researcher.

The measures of the Robbins and Klee clinical assessment of oropharyngeal motor development in young children (RK: Robbins & Klee 1987) were also consulted (see Cleland et al., 2010 for more results and discussion on this measure in these children). The Robbins-Klee measure is based on a series of oral motor tasks (i.e. a combination of speech and non-speech movements) and is scored on a scale of 0-2, where 2 is adult like, 1 is approaching adult-like or 0 = absent.

3.5 Perceptual data analysis

All repetitions of the wordlist were annotated at word level for auditory transcription, and then segmentally (only the attempts at the target consonants) for the EPG measures (both using AA). Perceptual data was transcribed and three measures performed on the auditory transcription:

- Perceptually acceptable score

- Phonetic error
- Error pattern analysis

3.5.1 Data transcription

All attempted productions of /s/ in ‘a sun’ and /ʃ/ in ‘a sheep’ were transcribed auditorily by the PhD researcher (T1). Further transcribers were recruited for analysis of /s/ and /ʃ/. Each transcriber was provided with a randomised set of ‘sun’ or ‘sheep’ productions from a number of individuals (see below). The transcribers were all aware that the children had Down’s syndrome, were aware also of the target word and were asked to transcribe only the initial sound in the word. Inter-rater reliability was performed on 60% of the data for /s/, 60% of /ʃ/ data. Intra-rater reliability was performed on a randomly selected 40% of the data for both /s/ and /ʃ/.

For the analysis of /s/ the MRC SLT (T2) transcribed 15 randomly-selected participants (150 tokens of /s/ in ‘a sun’). A third transcriber, a research SLT (T3), was recruited and transcribed the same 15 participants. Inter-rater reliability of broad transcriptions was 67% between the 3 transcribers (with 81% between T1 and T2, 77% between T1 and T3, 70% between T2 and T3). Intra-rater reliability for narrow transcription of /s/ was 75% (this was performed 8 years after the original transcriptions). The inter-rater reliability of broad transcription of /ʃ/ was performed by T2 and another research SLT (T4). T2 transcribed 15 randomly-selected participants, amounting to 150 tokens of /ʃ/ in ‘sheep’. T4 transcribed the same 15 participants. Inter-rater reliability was 51% between all three transcribers (with 68% between T1 and T2, 66% between T1 and T4 and 54% between T2 and T4). The low reliability score with T4 may be related to the level of experience of the SLT (a recent graduate). The transcriber also complained of problems hearing some of the data after they submitted the transcriptions. Intra-rater reliability for narrow transcription of /ʃ/ was 61% (this was also performed 8 years after the original transcription). Overall, the productions of target /ʃ/ were more problematic than those of target /s/. An agreement between any two transcribers was taken as the accepted transcription. In the case of disagreements, a consensus procedure (Shriberg, Kwiatkowski & Hoffman, 1984) was not plausible due to the availability of the other transcribers. In such cases, the PhD researcher returned to the transcriptions and the data to make a final decision.

The MRC SLT provided a more detailed transcription than the other transcribers which was extremely helpful but then also difficult to decide whether some allophonic differences would make a production perceptually acceptable or not. In order to decide this, two SLTs were consulted to establish what allophonic productions of /s/ and /ʃ/ would be considered perceptually acceptable and what would not. While some allophonic differences are atypical (affrication of plosives) and not identified in socioeconomic studies of Scottish English, they may not be considered a target for therapy and subsequently, advice was to treat as perceptually acceptable. The auditory analysis was used in the following perceptual measures and consulted for EPG analysis of only perceptually acceptable productions of speech data.

3.5.2 PTA measure

The auditory transcriptions were used to provide a perceptually acceptable target sound measure (PTA). This is a percentage score calculated for the three speaker groups (DS, TD and AD) for word initial /t/, /s/ and /ʃ/. The PTA score was used as an overall measure of the participants' ability to produce the sounds but the score was also useful when measuring aspects of articulation using the EPG measures. Individual variability of PTA scores was calculated using a between-speaker co-efficient of variation (COV) measure.

3.5.3 Phonetic Error analysis

A percentage consonants correct (PCC) measure, similar to the PTA above, is one of the most common ways of representing speech production in development research. And while it provides information about the phonological system it does not give insight into the articulation of the speech sounds. Edwards and Beckman (2008:14) indicate that they are strongly opposed to the use of PCC as a single measure in clinical speech research, stating that "we cannot base clinical or research decisions about consonant accuracy solely on transcriptions of consonants as correct or incorrect".

Another method for calculating, more accurately, the perception of the target sound is to assign a score for each error relating to voicing, place and manner. Hall et al. (1998) cited in Carter and Edwards (2004) assign a negative value to each error (-1 for a voicing error, placement error or manner error). This provides a score that illustrates small differences between the target and the production. In this study a different scoring system was used for a similar purpose. The intention here was to identify whether place of articulation, manner of articulation, or voicing was a particular problem for the speaker groups. The scoring system assigned a score for each target production based on these three features. This gave a maximum score of three for each production (or 30 for all repetitions). If the target sound was omitted then a score of zero was applied. These scores were converted to percentages to create a phonetic error (PE) score.

3.5.4 Error pattern analysis

In order to compare results with many of the previous studies of speech in DS, the perceptual results were then subjected to an error analysis where pattern types were assigned to the incorrect productions of /s/ and /ʃ/. This analysis was performed to provide data similar to the typical phonological process analyses evident in previous studies of speech production difficulties in DS (Bleile & Schwarz, 1984; Rupela et al., 2010; Stoel-Gammon, 1980; van Borsel, 1996).

The total number of patterns for the DS and TD groups was calculated and percentages of each pattern presented. The patterns identified are presented in Table 3-4. Patterns are identified as either typical or unusual, based on Dodd et al (2002). The other patterns identified follow those presented in Cleland et al. (2010) and are supplemented by patterns relating to substitution types.

3.5.5 Statistical analysis

3.5.5.1 Analysis of perceptual group differences

For the PTA measure a set of non-parametric Mann-Whitney U tests were run to determine if there were statistically significant differences between the three groups (DS, TD and AD) for each target sound. Non-parametric tests were chosen as a result of the small sample sizes in the control groups and the occasional non-normal distribution of data.

Typical patterns (Dodd et al. 2002)

Stopping	Replacement of fricatives with stops
Fronting	Place of articulation is moved to more anterior position
Voicing	Prevocalic voicing

Unusual error patterns (Dodd et al. 2002)

Backing	Place of articulation is moved to a more posterior position
Initial consonant deletion	Deletion of a word-initial consonant
Affrication	Interpreted here to indicate replacement of stops or fricatives with affricates

Other error patterns identified

Dentalisation	Target sound substituted by a dental fricative
Lateral+Central	Target sound substituted by lateral + central manner of articulation
Palatal	Target sound replaced by a palatal sound
Velar	Target sound replaced by a velar sound
Rhotic	Target sound replaced by a rhotic sound
Lateralisation	Target sound replaced by a lateral fricative
Debuccalisation	Target sound replaced by a glottal fricative

Table 3-4: Error pattern names and definitions. Typical and unusual error patterns and definitions from Dodd et al. 2002. Other error patterns reflect phonetic substitutions.

When performing multiple tests a Bonferroni correction is applied. A new significance value was created by dividing 0.05 by the number of comparisons made (0.05/3 = 0.0167).

3.5.5.2 Relationship of perceptual measures with age

In order to investigate the relationship of the perceptual measures performed on the target sounds, and participants chronological ages, Spearman's Rho correlations were run on the PTA scores and chronological age (for DS and TD groups only). Further correlations were run on the typical error patterns identified from the error pattern analysis and chronological age.

3.6 EPG data analysis

EPG data was annotated and a series of spatial and temporal measures were performed. The following measures were performed on all attempted productions of /t/ in 'a toe', /s/ in 'a sun' and /ʃ/ in 'a sheep' for all participants in the DS, TD and AD groups. The same measures are performed on the perceptually acceptable tokens unless stated otherwise. Between-speaker variability was calculated for all measures by a coefficient of variation (COV), unless stated otherwise.

Spatial measurements:

- COG
- Whole total contact
- Variability
- Alveolar closure score
- Canonical analysis

Temporal measurements:

- Duration
- Temporal variability

3.6.1 Annotating EPG data

The EPG analysis was performed in Articulate Assistant^{TM} which provides many different measures that can be applied to the EPG dataset. Some measures involved spatial information (COG, variability, whole total contact) and others involved timing (duration). Before any measures can be performed the data is annotated following a system designed for the purposes of the project. This allows grouping of the data whenever required (e.g. perform an analysis on only word initial /s/). In this project the annotated regions were labelled by target sound, number of repetition and word (e.g. '/s/ rep1 sun'). Not all speakers attempted a production of the target sound that could be annotated (either nothing was produced, a different word was produced or a speech sound that has no lingual-palatal contact, e.g. /p/). For example for the first repetition of 'a toe', DS01 names it as 'a finger'. This repetition was then removed from analysis. This meant that there wasn't always an annotated section for all target sounds.

The target sounds were annotated from the EPG and acoustic information in the AA software. Each attempt at the target sounds was annotated according to the articulatory characteristic of the actual production. For example, if the speaker produced a sibilant then the articulation region was annotated from the acoustic signal (onset to offset of friction). If the speaker produced a stop consonant then the period from beginning of closure to release was annotated from the EPG patterns (for beginning of closure) and the acoustic signal (for release of closure) (Dagenais et al., 1994). If the release was not clearly represented on the acoustic signal, the EPG frames were also consulted. If the speaker produced an affricate then the articulation region was annotated in two parts, the beginning of closure of the stop to the acoustic release and from the acoustic release to the offset of friction. Often, it was difficult to work out what the attempted production was and therefore how to annotate it. In those occasions the annotation was based on either any acoustic information that may represent a production or a change in EPG patterns immediately before the vowel. The sounds annotated had to have some acoustic or articulatory presence that could not be attributed to breathing or unconnected tongue movements.

A straightforward sibilant annotation of /s/ is shown in Figure 3-5. This was heard as [s] and was also acoustically typical of /s/ and therefore easy to annotate from the acoustic pattern (high frequency friction noise).

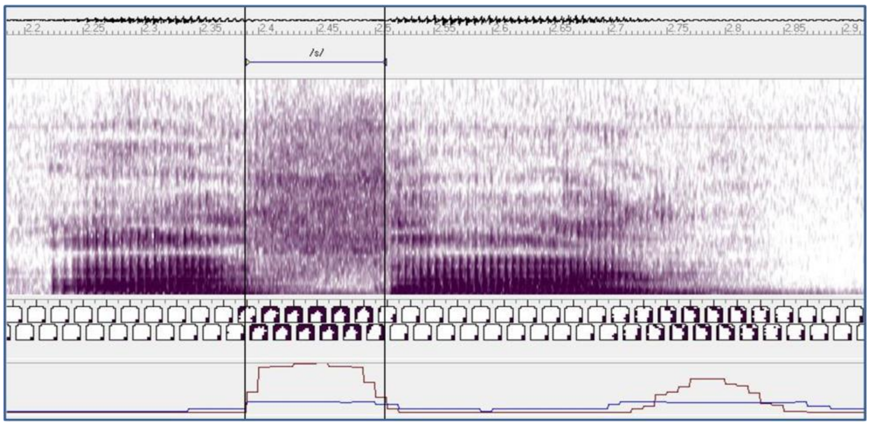


Figure 3-3: Target /s/ in 'a sun', heard as [s]. Annotated from the onset and offset of frication identified from the acoustic trace

Figure 3-4 below shows the annotation of target /s/ when the production was realised as a [t]. This annotation was based on the EPG frames which show alveolar closure and then a release (which is not that clear from the acoustic information). It appears that the release is acoustically produced about 2/3ms into the closure of the [t] suggesting that the acoustics and EPG information is misaligned. This may be due to the presence of pre-aspiration during the production of [t]. As the nasal closure pattern (in WF position) of the EPG frames is correctly positioned with the acoustics this was discarded and the EPG frames were used as guidance for release of the plosive, not the acoustics.

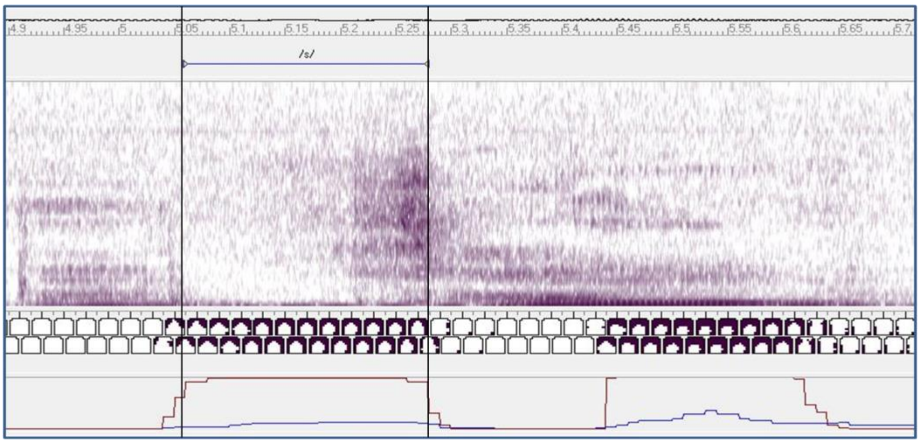


Figure 3-4: Target /s/ in 'sun', heard as [t], annotated from EPG and acoustic information - first frame of complete closure to first frame of closure release, and acoustic burst.

Figure 3-5 shows a case where the auditory information had to be used alongside acoustic and EPG data. This production of target /s/ was heard as an alveolar affricate. However, the plosive portion of the affricate is not produced with complete alveolar contact therefore the annotation starts at the maximum frame of closure for the plosive portion. The release of the affricate was determined by viewing the acoustic information.

From the annotated regions defined at this level, particular points from the annotations can be selected for analysis. At the defined points, AA can be instructed to measure duration and various contact measures (variability, COG, contact).

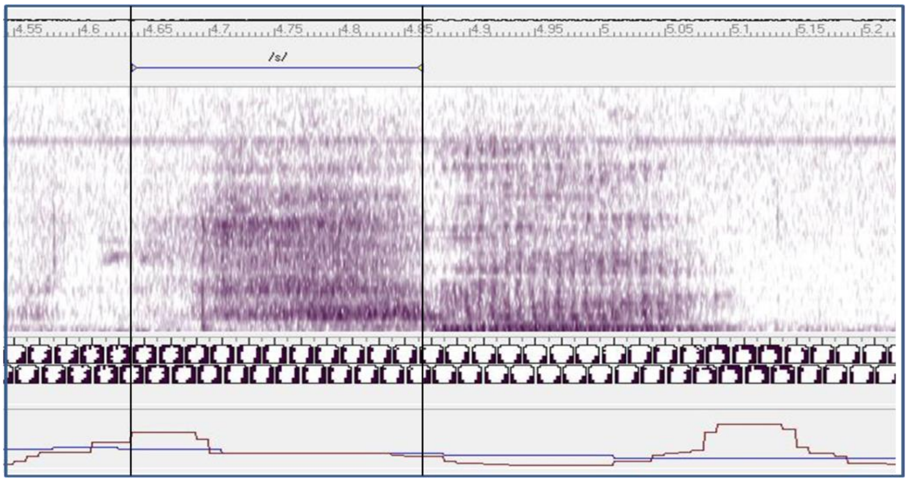


Figure 3-5: Target /s/ in 'sun', heard as [ts], annotated from both EPG (for onset of plosive portion) and acoustic signal (for friction offset).

3.6.2 Centre of Gravity (COG)

Centre of gravity (COG) is an index that measures the weighting of tongue contact on the EPG palate. It provides a score calculated from the position (anterior or posterior) of tongue contact on the different rows of the palate. The COG score is calculated using this formula:

$$\frac{0.5*r8+1.5*r7+2.5*r6+3.5*r5+4.5*r4+5.5*r3+6.5*r2+7.5*r1}{62}$$

Where *r*8, *r*7, *r*6, etc. represent row 8, row 7, row 6, etc. and 62 is the total number of electrodes on the palate. Row 8 is the back row and row 1 is the front row. COG is generally used to measure the differences between the articulation of anterior and posterior articulations (Gibbon, Hardcastle & Nicolaidais, 1993). A numerical score (from 0-8) is given which represents the greatest number of activated electrodes in the front/back dimension. A high COG score represents an anterior articulation and a low COG score a posterior articulation. Typical alveolar articulations have a COG of 4-6 and velar articulations are usually between 0.5-2 (Gibbon & Wood, 2002). Recent work by Gibbon and Lee (2011) found that COG is also sensitive to smaller differences in place of articulation (POA). In their study, Gibbon and Lee (2011) used COG to show differences in POA in typical /s/ and /ʃ/ production, noting that within speakers there are clear differences between the two sibilants (with /s/ showing a higher COG value than /ʃ/). They stress that this is within-speaker only, as frequency values will differ individually.

For this study the COG measurement was taken from the first frame of maximum contact of the annotations from all attempted productions of /t/, /s/ and /ʃ/ and of all perceptually acceptable productions. Means and standard deviations were calculated for each individual's production of each target sound. The mean difference between the COG scores for the 2 sibilants was calculated to represent the articulatory distance between the two.

3.6.3 Whole total contact measure (WTM)

Whole total contact is an index that measures the amount of contacted electrodes at the selected time point. The whole total measure calculates the number of contacted electrodes and divides that by the number of electrodes on the palate. The measure was calculated from the first frame of maximum contact and is presented as a mean.

3.6.4 Spatial variability measure (OSVar/PSVar)

The AA software provides a spatial variability index to calculate the stability of articulation gestures (Farnetani & Provaglio, 1991), providing a numerical value ranging from 0-50 (where 0 indicates no variability and 50, absolute variability). Wrench (2008; 21) describes the calculation of the index as follows: "the percent frequency of activation of each contact across frames is measured. For each contact, 100% and 0% activation frequency represent invariance and are assigned a variance index of 0. The variability index increases as contact frequency approaches 50%, which is assigned a maximum index of 50. The overall variability index is calculated in two forms:

1. by summing the index values for all contacts with more than 0% contact and dividing by that number of contacts.
2. by summing the index values for all contacts and dividing by 62."

The variability index can provide a measure of instability (or inconsistency) of EPG contact across one annotation or across many annotations. In this study the index was calculated from the frame of maximum EPG contact within the annotated region of all the attempted productions of word initial /t/, /s/ and /ʃ/ in the wordlist data in order to assess within-speaker variability of articulation. High values of the variability index are interpreted as showing inconsistency of production (Holm, Crosbie, & Dodd, 2007). The measure of inconsistency allowed for a measure of an inconsistent production of the target sound. A high variability index in this context would likely be indicative of a participant whose attempts were noticeably perceptually different and also phonemically different. This will be referred to as the overall spatial variability score (OSVar).

Another spatial variability measure was calculated from only the perceptually acceptable tokens of the target sounds. This measure will be referred to as the perceptually acceptable spatial variability measure (PSVar) as it reflects the variability in articulation of productions deemed to be phonemically similar (perceptually).

3.6.5 Canonical analysis (CA)

Designed by Alan Wrench of Articulate Instruments Ltd, Canonical Analysis is a type of Linear Discriminant Analysis (LDA) which is a statistical technique that attempts to find a set of features that characterises or separates a group of objects. Distances are calculated from a trained set of features, measured in the *Mahalanobis* metric. LDA has previously been used with speech recognition studies (Kumar & Andreou, 1998) and has only recently been employed with EPG data. The benefits of LDA (compared to other comparison techniques, i.e. Principal Component Analysis (PCA)) are that it is comfortable with unequal frequencies and randomly generated test data.

Measurements of the whole EPG palate have been attempted by various researchers in the past (Guzik & Harrington, 2007; Holst, Warren & Nolan, 1995; Nguyen, Marchal & Content, 1996). For example, Holst et al. (1995) used neural nets in their analysis of English sibilant production. Similarly to the CA approach, a neural net can be trained on patterns on input data (in this case the on/off patterns of the EPG palate) from typical productions of /s/ and /ʃ/ from sentences. In total, Holst et al. (1995) trained the neural net on 1375 frames which were used in the training cycle for an average of 50 times. The CA program used here was not trained on the same pattern more than once as the typical data was limited. Ideally the system would include a range of as many variations of /s/ and /ʃ/ articulations that are used in English.

In order to distinguish the articulatory features of particular speech sounds, the CA measure is trained with many samples of typical productions of different articulation patterns (this may be limited to the typical data available and may not include disordered articulations, say alveolar lateral fricatives) (Wrench, 2008). For this project the CA measure was trained on /t/, /s/, /ʃ/ and /k/ patterns (limited by EPG data available). The training data aims to reflect as many of the different articulation patterns considered acceptable for a particular sound. No difference is recognised for the articulations of voiced/voiceless pairs therefore patterns for /s/ and /z/ (for example) are bundled together. An uneven amount of tokens for each training category was available (Table 3-5) from the adult data collected in this project and data from the ACCOR database (Marchal & Hardcastle, 1993). The training data was established from midpoint frames from annotated typical adult productions of the target sounds.

Pattern type	No. of trained tokens
t/d	120
k/g	101
s/z	106
ʃ/ʒ	13

Table 3-5: Number of typical patterns within each canonical analysis training group

Table 3-5 above presents the amount of typical patterns accumulated for the training data. With 4 trained reference sets, the tested data can be compared to 4 different articulation patterns. These 4 reference sets can be illustrated on a 2D graph as below (Figure 3-6).

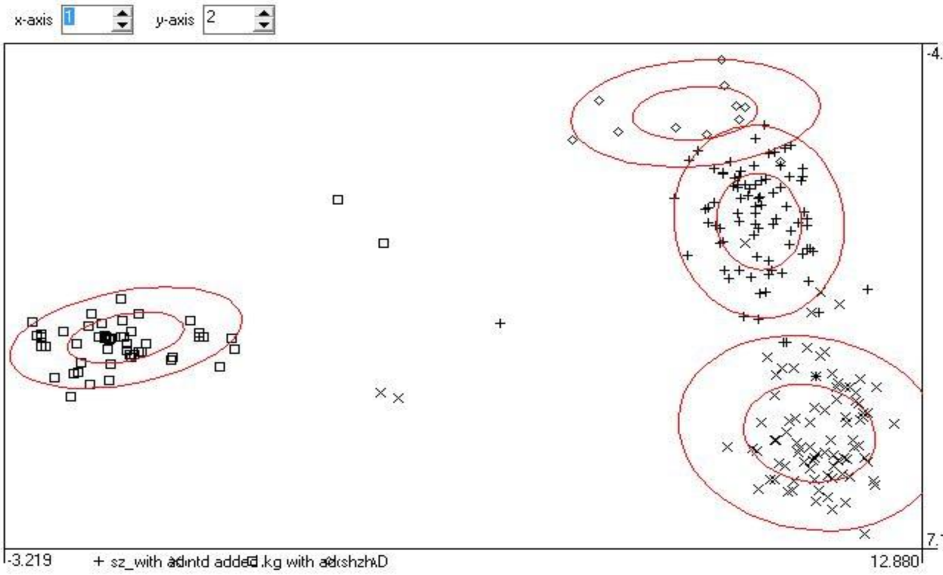


Figure 3-6: 2D graph of the training datasets for alveolar sibilants (+), alveolar plosives (×), velar plosives (□) and post-alveolar sibilants (◊). Ellipses represent 1 and 2 standard errors.

3.6.5.1 Performing the analysis

Palate values (combinations of 1s and 0s from the individual electrodes) were calculated from the midpoint of all productions of the target sounds (these can be easily extracted from AA). This resulted in a single file for target /s/ and target /ʃ/ per speaker. These files are then tested against the reference (trained data) sets previously provided. The initial output provides a 2D space with all tokens of the tested data plotted against the reference data.

The CA technique then gives the option to output the Mahalanobis distances of the tested data from the trained data. Each production of each target sound for each speaker is given a distance score from both the trained /s/ data and the trained /ʃ/ data. It is the Mahalanobis distances that will be presented in the results section for this measure.

3.6.6 Duration and temporal variability

Duration was calculated from the annotated regions of the target sounds. Analysing duration can be complicated, as speech rate (and other factors) can affect the duration of the production. Therefore, these measures were calculated in order to assess levels of temporal variability. A coefficient of variation (COV), as a relative measure, was employed to assess temporal variability (Cheng et al., 2007; Koenig et al, 2008; McAuliffe et al., 2003). The mean and standard deviation of each speaker's ten repetitions were used to calculate the individual's COV measure. This temporal measure is included to see whether children with DS show similar levels of temporal variability to the typically developing control group, or higher levels. The duration of the annotated sounds considered perceptually acceptable for each target sound was measured and the mean duration for each sound was calculated. Perceptually acceptable tokens were chosen in order to compare the results with previous studies on sibilant length.

3.6.7 Statistical analysis

3.6.7.1 Analysis of group differences

For each EPG spatial and temporal measure, non-parametric Mann Whitney U tests were run to determine if there were statistically significant differences between the three groups (DS, TD and AD) for the target sounds. Non-parametric tests were chosen as a result of the small sample sizes in the control groups and the occasional non-normal distribution of data.

When performing multiple tests a Bonferroni correction is applied. A new significance value was created by dividing 0.05 by the number of comparisons made (0.05/3 = 0.0167).

3.6.7.2 Relationship of EPG measures with age

In order to investigate the relationship of the EPG measures (OSVar, PSVar, COG, WTM and temporal measures) and the participants' ages, Spearman's Rho correlations were run on the scores and chronological age (for DS and TD only).

3.7 Case study data analysis

The case study chapter of this thesis will review individual scores from all the measurements mentioned above. In addition, measurements of the following will be analysed:

- EPG Alveolar closure score
- DDK rate and accuracy

3.7.1 Alveolar closure measure

The Articulate Assistant™ Alveolar closure measure was calculated for the /s/ and /ʃ/ productions for only the speakers selected for the case studies. This measure provides a score for the connectivity between the right and left sides of the palate. The higher the closure score, the more contact between the two sides of the palate (Articulate Instruments™, 2008). This then relates to the width of the groove presented in the articulations of the target sounds. A narrow groove will have a higher closure score than a wide groove but complete closure will provide an even greater score. The scores approximately relate to the following (Alan Wrench, personal communication, 2014) in Table 3-6.

The anterior closure was calculated across each annotation of target /s/ and /ʃ/ to assess variability in groove width in the 5 speakers selected for Chapter 7 (scores taken from the first and last frames of the EPG annotation, including 6 equally spaced points within the annotation). The same measures were taken from the AD productions of /s/ and /ʃ/ and a mean measure of 8 equally spaced points will be presented alongside the DS data. This measure presents a look at the dynamic pattern of articulation of sibilants in the speaker groups.

Closure Score	EPG contact
0.9	1 row of complete closure
1.0	2 rows of complete closure
5.0	1 row with a 2 contact groove
6.0	2 rows with a 2 contact groove
6.5	1 row with a single contact groove
7.5	3 rows with a single contact groove

Table 3-6: Articulate Assistant Closure scores and the related EPG lingual palatal contact they represent

3.7.2 DDK analysis

Rate measurements (maximum syllables per second) and accuracy were calculated from the DDK tasks for the 5 speakers that were chosen for the case study chapter (Chapter 7). The measurements for the DS group were completed by the SLT on the MRC Project. Subsequently, the PhD researcher completed the rate and accuracy measurements of the TD participants for comparison. From each measurement, a maximum rate of repetition was calculated for the monosyllabic tasks and multisyllabic tasks. This resulted in a mean score being calculated for the TD group overall to be used for comparison with the individual's scores. Accuracy was calculated by transcribing the first imitation of the target syllable or sequence and a score of one was applied for an acceptable imitation and zero for inacceptable, scores were then converted to percentages (McCann & Wrench, 2007).

3.8 Descriptive pattern analysis

The annotated regions of the target sounds, /t/, /s/ and /ʃ/ were analysed visually (similar to Bartle-Meyer et al., 2009) and the most prominent pattern was labelled accordingly, following the pattern taxonomies presented in Chapter 4. At times the prominent pattern was established by counting what the majority of frames within the annotation displayed. This analysis was performed on all data from the DS and the TD groups. A comparison was made between the patterns used by the two groups. All patterns used by the TD group were considered to be representative of typical speech behaviour as they were present in the speech of a group of typically developing children. The creation of the taxonomy for /t/ was guided by the MRC team (but analysis performed by PhD researcher), however the sibilant analysis and creation of the sibilant taxonomies were solely completed by the PhD Researcher (detailed taxonomy descriptions are presented in Chapter 4).

Following the DS and TD analysis, the same process was applied to the AD data to provide a range of standard typical patterns from a stage of stability in speech articulation. The TD speakers were still stabilising the articulations of the sibilants and may be producing some different patterns at this stage. Also, it was felt that there was a lack of detailed information in the literature about the range of typical articulation patterns for the post-alveolar sibilant.

The pattern analysis was performed on all productions of the target sounds and then results divided into smaller groups of perceptually acceptable and error-full productions to identify the range of articulation patterns that could yield an acceptable (or error) production. Percentages were calculated for all pattern types for all three speaker groups. Only one pattern per annotation was identified and a percentage of pattern use was calculated.

3.8.1 Statistical analysis

3.8.1.1 Analysis of EPG descriptive pattern group differences

For the EPG descriptive measures a set of non-parametric Mann-Whitney U tests were run to determine if there were statistically significant differences between the three groups (DS, TD and AD) for the amount of typical patterns identified for each target sound. Non-parametric tests were chosen as a result of the small sample sizes in the control groups and the occasional non-normal distribution of data.

When performing multiple tests a Bonferroni correction is applied. A new significance value was created by dividing 0.05 by the number of comparisons made (0.05/3 = 0.0167).

3.8.1.2 Relationship between EPG descriptive patterns and age

In order to investigate the relationship of the perceptual measures performed on the target sounds, and participants chronological ages, Spearman's Rho correlations were run on the percentage of typical pattern scores and chronological age (for DS and TD groups only).

3.9 Group versus case study data analysis

This study combines a group and case study analysis approach. Generally speech articulation research uses small group or single subject designs, providing more detailed analysis of individual articulation ability than provided in large scale studies

(Bernhardt et al., 2013). This was the main motivation for the inclusion of case studies in this study. However, the narrow focus of case studies limits the generalisability of findings and it has been noted that case studies are vulnerable to selection bias (Irwin, Pannbacker & Lass, 2014). In contrast, group designs allow findings to be generalised to the population being studied however, to do so this also assumes homogeneity of the group members. Another advantage of a group design is the possibility of investigating potential causal relationships. The high number of participants available for research in this study (25) may be small in comparison to many group studies but provides a means to investigate causal relationships. The case study data will be used to support the overall group findings and to highlight the heterogeneous nature of the DS group, by identifying individual characteristics (Perkins & Howard, 1995).

3.10 Statistical analysis

Some basic statistical measures were completed within Microsoft Excel. This involved calculations of means, standard deviations and coefficients of variation. All quantifiable data was entered into IBM SPSS Statistics 21 which was used to run statistical measures (Mann Whitney U tests, Spearman's Rho correlations) on the perceptual and EPG (quantitative and descriptive) measures results. Alongside mean scores and standard deviations, descriptive statistics are represented by median and interquartile range (IQR) values. Boxes represent the median, and 25th and 75th values. Whiskers represent the highest and lowest data scores that are not outliers.

4 Methodology Part Two – Descriptive Analysis

4.1 Introduction

This chapter presents the methodology behind the classification of patterns involved in the pattern analysis. It is presented in a separate chapter as it involved an initial analysis approach in order to create the target sound pattern taxonomies described in detail below.

The chapter will present taxonomies for each target sound (/t/, /s/ and /ʃ/), an explanation of the pattern types and the justification for their inclusion. These explanations will be presented by target sound but in the case where patterns appear in more than one taxonomy, the pattern description will not be duplicated.

4.2 Creating pattern taxonomies

The annotated Electropalatographic (EPG) data was analysed visually and the most prominent patterns were identified from the annotated regions. A taxonomy for /t/ was created initially by the PhD researcher and adapted by co-authors on the MRC project (see Timmins et al., 2011). This was a difficult task and required continuous discussion. The sibilant taxonomies were created by the PhD researcher alone. For all target sounds (/t/, /s/ and /ʃ/), the pattern analysis was completed solely by the PhD researcher. The patterns included in the taxonomies are all from data within this study. No inter-rater reliability was performed on the categorisation of these patterns.

The EPG frame is presented in Figure 4-1 below. Each frame represents tongue-palate contact every 10 milliseconds of recorded speech. The frame shows individual rectangles (62) representing each electrode on the EPG palate. These are placed in 8 rows from the front of the palate to the back. The first row contains 6 electrodes and the next seven contain 8 electrodes. In typical speech production alveolar and post alveolar sounds are represented by contact with the first four rows on the palate (at the top). Palatal and velar sounds have most of their contact on the back four rows (Wrench, Gibbon, McNeill & Wood, 2002). The pattern analysis is based on this normalised palate therefore any differences in palate shape dimensions are not reflected.

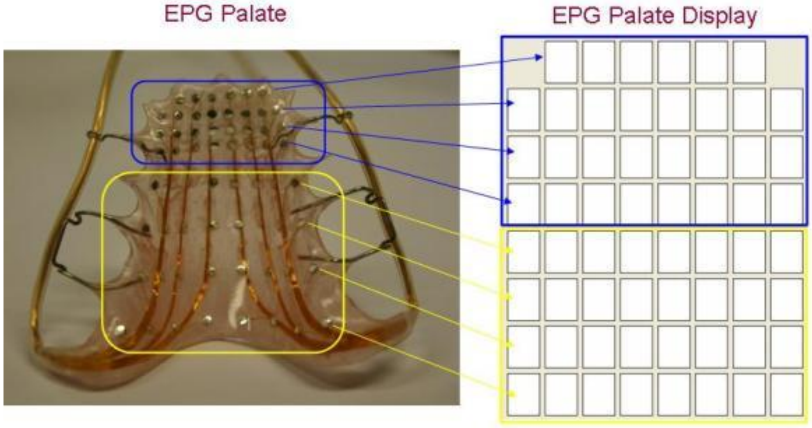


Figure 4-1: A typical EPG palate (left) with computer palate frame (right). Blue highlights anterior section of the palate, yellow is the posterior.

In this study, individual taxonomies for each target sound (/t/, /s/, and /ʃ/) will be presented. The pattern types described refer to the most prominent pattern across the annotation (i.e. not from a single time point). Following the taxonomies, descriptions of each pattern are presented.

4.3 /t/ taxonomy and pattern discussion

The taxonomy for /t/ production is presented below (Figure 4-2) with a short description of each pattern as identified in these data, along with an example EPG pattern from the same data. While the analysis (and example) is based on the most prominent pattern within the annotation, an asterisk is positioned above a single EPG frame that particularly illustrates the pattern described. This is a slightly adapted version of the taxonomy presented in Timmins et al. (2011).

4.3.1 Typical alveolar stop

This pattern was established from consultation of the typical speech data from the control group. From this analysis we concluded that a perceptually acceptable /t/ was produced with complete contact across the alveolar place of articulation (and possibly beyond, to row 4) with complete lateral bracing. This is more contact than is usually accepted for typical alveolar closure but it resulted in perceptually acceptable tokens for the typically developing (TD) group of speakers so it was accepted for this study. While there are variations in contact patterns for typical alveolar stops in different phonetic contexts, these sounds are identified by their horseshoe shape of lingual contact.

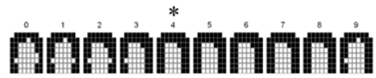
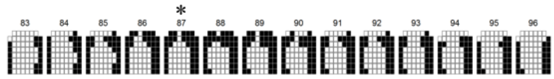
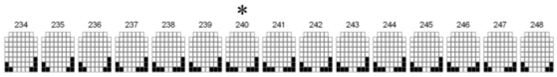
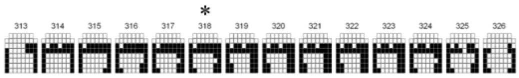
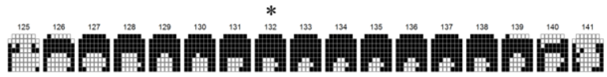
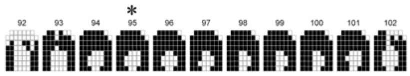
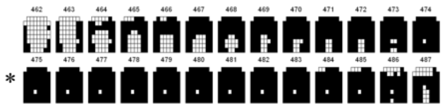
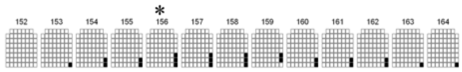
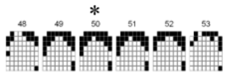
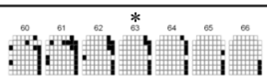
EPG Pattern Description	Example EPG pattern from annotated region
Typical alveolar stop: Alveolar closure (full closure in row 1, may extend to row 4) with lateral bracing. Typical horseshoe pattern.	
Incomplete closure: Incomplete anterior closure with lateral bracing	
Posterior articulation: Velar constriction (can include complete closure, or 1-2 contacts untouched) with no anterior closure	
Retracted anterior closure: Anterior closure with lateral bracing but at row 3 or further back	
Full anterior closure: Complete anterior closure from row 1 to row 5 with lateral bracing	
Double articulation: evidence of discrete anterior closure with simultaneous discrete velar closure	
Undifferentiated gesture: contact across palate as if tongue pushed up to palate with no evidence of separate control of tip/blade and body.	
Minimal contact: overall minimal tongue contact (with only contact at sides of palate)	
Anterior closure with lack of lateral seal: Complete closure at rows 1 or/and 2 with lack of complete lateral bracing	
Lack of lateral seal: Incomplete lateral bracing	

Figure 4-2: Taxonomy for /t/ pattern analysis. With description and example provided. * indicates specific example frame of described pattern type

4.3.2 Incomplete closure

The incomplete closure pattern was similar to an acceptable pattern for the typical alveolar fricative (see 4.4.1). Incomplete closure for target /t/ production is not a common finding in typical speech production (though Cheng et al. (2007) found this pattern in their child data). In EPG research of disordered speech production, incomplete alveolar closure for target /t/ has been found in data from speakers with Apraxia of Speech (AOS) (Bartle-Meyer et al., 2009).

4.3.3 Posterior articulation

Posterior articulation is similar to the process of backing found in previous EPG studies (e.g. Gibbon, 2004). This articulation represents velar closure without any anterior closure (as would be typical for a target /k/ or /g/). The posterior closure is defined as 2-0 contacts untouched at the velar place of articulation. Complete velar closure is rare in typical productions of velar plosives as the EPG palate is created to sit on the hard palate (not the velum). This pattern was included to represent velar productions of the target sounds. Posterior articulations of anterior targets is not common in typical speech development but noted in speech disorder populations, for example, Hardcastle et al. (1987) note this for WI /s/ in children with functional articulation disorders and others have identified this in children with cleft palate (Gibbon & Hardcastle, 1989).

4.3.4 Retracted anterior closure

Retracted anterior closure represents the production of complete anterior closure with lateral bracing but situated further back on the palate than typical productions (for /t/ this would be row 3 or further back, i.e. post-alveolar or palatal). This may also indicate presence of retroflex articulation but EPG is unable to provide details of the area of the tongue involved in the articulation. Retracted anterior closure patterns have been noted in studies of speech in people with cleft palate and cerebral palsy (Gibbon, 2004; Nordberg et al., 2011).

4.3.5 Full anterior closure

This pattern was defined as complete anterior closure greater than the typical closure pattern. Precisely, this was complete closure from rows 1 to 5, and further back. This pattern is an example of increased contact. Increased contact has been noted in previous studies of Down's syndrome (DS) (Hamilton, 1993) and frequently in EPG studies of cleft palate speech (Gibbon, 2004; Howard, 2004).

4.3.6 Double articulation

Double articulation is identified as complete closure in the alveolar region and increased velar closure (this may not be complete due to the limits of the EPG range, so here it is considered velar if there is a gap of 2 electrodes or less). Double articulations have been found in many EPG studies for target plosives (Bartle-Meyer, 2009; Dent et al., 1992; Hardcastle, 1987; Hardcastle et al., 1989; Whitehill, Stokes, Hardcastle & Gibbon, 1995) particularly in cleft palate (Gibbon, 2004). Nordberg et al (2011) found double articulations for target /t/ in speakers with cerebral palsy, similarly Gibbon and Wood (2002) found double articulations in a child with mild cerebral palsy. Double articulations have also been noted for target /s/ productions, for example, Bartle-Meyer et al. (2009) found double articulations for productions of /s/ in speakers with AOS.

4.3.7 Undifferentiated gesture (UG)

Undifferentiated lingual gestures have been described as articulations where there is a high level of tongue-palate contact (Gibbon, 1999). In the example of a target alveolar sound, an undifferentiated gesture would refer to an articulation where not only is there lingual contact at the alveolar region but this also extends to the palatal and, possibly, velar regions. In these cases there is no evidence of separate control of the tongue tip/blade and the tongue body. Gibbon (1999) reports that target sounds considered perceptually correct have been noted to be produced with undifferentiated gestures in a few studies (Dagenais et al., 1994; Gibbon, 1990; Gibbon et al., 1995; Hardcastle et al., 1987). UGs have been established as a feature of articulation/phonological disorder (Gibbon et al., 1995, Goozee et al., 1999) and are noted to be a reflection of motor difficulties.

4.3.8 Minimal contact

This pattern is identified as a lack of lingual palatal contact. This pattern has been identified in studies of cleft palate speech (Dent et al., 1995; Gibbon et al., 1998) and noted in speakers with cerebral palsy (Nordberg et al., 2011). Gibbon et al. (1996) note this pattern in children with sibilant difficulties, finding minimal tongue-palate contact when the children produced pharyngeal fricatives for target alveolar and post-alveolar sibilants.

4.3.9 Anterior closure with lack of lateral seal

This is not a common pattern in the literature but occurred frequently enough in these data to warrant a separate category. This category includes patterns where there was complete closure in rows 1 and/or 2 with some lateral contact. However, the detectable lateral contact was either broken and/or unilateral. Gibbon (2008) notes a similar pattern in a child with a functional articulation disorder. Roberts et al. (2002) note this pattern in impaired alveolar sibilants, referring to it as a 'lateral gap'. McLeod (2006) also identifies this pattern in typical productions of /n/ in 2 of 8 speakers. In a study of lateral /s/ production, Gibbon and Hardcastle (1987) discuss the issue of missing lateral contact on the EPG frame. They suggest that an incomplete lateral seal may be the result of tongue contact outside the electrodes (due to lateral spreading of the tongue) or the lateral seal may be made by contact with the teeth. This pattern (and *lack of lateral seal*) may then be considered a normal articulation pattern (and is also found in Cheng et al (2007)).

4.3.10 Lack of lateral seal

This is a similar pattern to *anterior closure with lack of lateral seal* but in this case, there is no anterior closure. This could also be described as unilateral bracing, where there is only lateral contact down one side of the palate. Again, this pattern is not represented in the literature, though it may be similar to the 'lateral gap' pattern found in Roberts et al. (2002). Hardcastle and Edwards (1992) also report a similar pattern for target /s/ and /z/, typically reflecting articulatory undershoot.

4.4 /s/ taxonomy and pattern discussion

The taxonomy for /s/ production is presented below with a description of each pattern as identified in these data, along with an example EPG pattern from the same data.

4.4.1 Typical alveolar fricative

This category of patterns represented the typical narrow groove at the alveolar place of articulation (rows 1 and 2). A narrow groove is one that is 1-3 electrodes wide (Gibbon & Hardcastle, 1987). A groove width of 3 electrodes has been noted for /s/ production in children from 6yrs to 17yrs (Cheng et al., 2007). This category also included the more detailed category of asymmetrical groove. Asymmetry is commonly found in production of alveolar sibilant grooves e.g. Dagenais et al. (1994) note that few productions of alveolar and post-alveolar sibilants in their typical adult data were produced with grooves along the anterior/posterior midline. McLeod, Roberts and Sita (2003) also find asymmetrical groove patterns in their study of voiced and voiceless alveolar sibilants.

4.4.2 Wide groove

This is another pattern reflecting the presence of a groove at the alveolar place of articulation but this time the groove is twice as wide as the typical pattern mentioned above (4 electrodes or more). The pattern of articulation may look typical but the width of groove may be an important detail of articulation. Studies have found that the groove width may affect perception of the target sibilant therefore it may be important to distinguish a wider groove pattern from a narrow groove.

4.4.3 Lateral fricative

Lateral productions of fricatives are fairly common in speech articulation disorders (Hardcastle et al., 1991), however the exact nature of these patterns is difficult to define (see 1.4.1 for further discussion). There are many different patterns identified for a perceived lateral fricative in atypical data (Gibbon et al., 1995; Gibbon, 1999). As noted in Howard (1995), the obstruction for lateral fricative production is not always alveolar, and lateral friction can be produced from a range of places of articulation and widths of closure. This suggests that defining a canonical pattern for analysis (based on IPA descriptions) may not be adequate for identifying lateral fricatives. In this case, however, the lateral fricative pattern defined in Figure 4-3 is based on the IPA description and reflects complete closure across the alveolar region and beyond. Lateral air is released at the posterior region of the palate and a lack of lateral bracing is required at the back 2 rows (though there may be a lack of contact further forward). This pattern may be similar to *Full Anterior Closure* with the lack of lateral seal being hidden behind the velar contact region. These patterns will be discussed in more detail in Chapter 8.

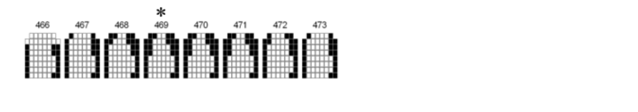
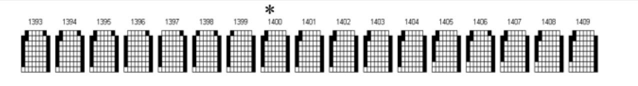
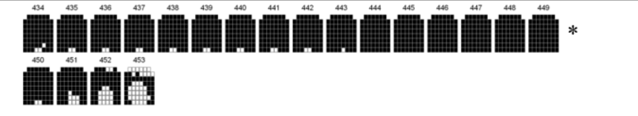
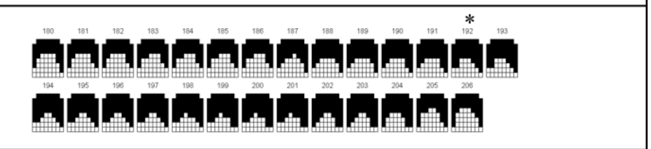
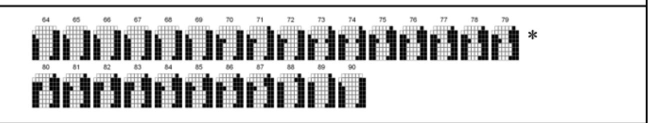
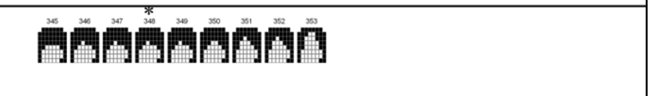
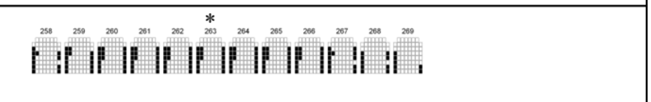
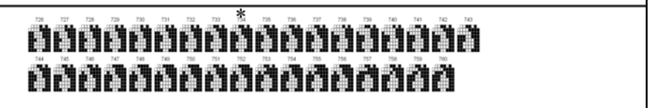
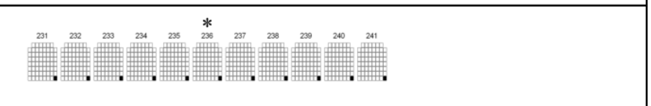
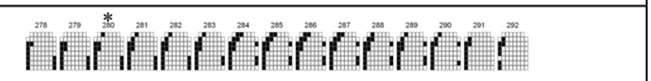
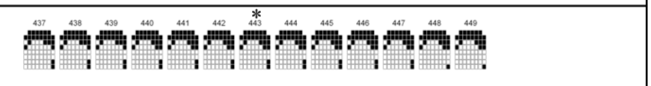
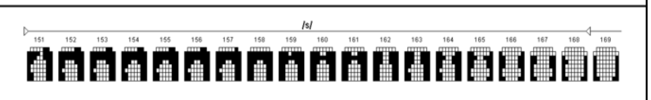
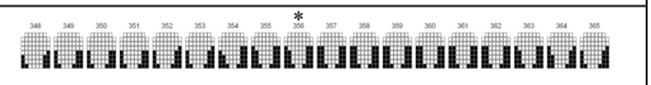
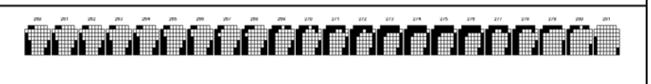
EPG Pattern Description	Example EPG pattern from annotated region
Typical alveolar fricative: Narrowest groove at alveolar region (rows 1-2) with lateral bracing. May be asymmetrical	
Wide groove: Narrowest part of groove 4 or more electrodes wide	
Undifferentiated gesture: contact across palate as if tongue pushed up to palate with no evidence of separate control of tip/blade and body.	
Lateral fricative: Complete anterior closure from rows 1-3 (and possibly beyond) with lack of lateral seal at velar place of articulation	
Retracted pattern: anterior groove with lateral bracing but at row 3 or further back	
Complete anterior closure: complete alveolar closure with lateral bracing	
Lack of groove: lateral bracing but no evidence of any narrowing	
Anterior groove + velar constriction: presence of grooving with simultaneous velar closure	
Minimal contact: overall minimal tongue contact (with only contact at sides of palate)	
Lack of lateral seal: Incomplete lateral bracing	
Anterior closure with lack of lateral seal: complete alveolar closure with incomplete lateral seal	
Affricate: clear evidence of period of complete closure followed by anterior groove	
Velar constriction with lateral contact: evidence of velar closure with lateral contact	
Articulatory drift: change of P.O.A. during closure phase (e.g. complete alveolar closure to velar closure,)	

Figure 4-3: Taxonomy for /s/ pattern analysis. With description and example provided. * indicates specific example frame of described pattern type

4.4.4 Retracted pattern

Although /s/ is generally defined as having a groove at the alveolar place of articulation, Cheng et al. (2007) analysed EPG patterns of adults and children and found that the place of articulation for the narrow groove was further back in younger children than older. The 6-7 year old group showed narrowing at rows 3 & 4 as did the 8-11 year old group. The 12-17 year old group displayed a more adult-like pattern with the narrow grooving appearing at rows 1 & 2. Due to this finding it is important to interpret this pattern as typical rather than atypical (though it was considered interesting enough that it was dealt with separately in the analysis).

4.4.5 Complete alveolar closure

This pattern is the same as *Typical Alveolar Stop pattern.* Complete closure of grooved sibilants has been noted in studies of both typical speech production and in data from speakers with speech difficulties. McLeod et al. (2006) identified this pattern of contact for /s/ production in typical speakers but it was suggested that the groove may have occurred between electrodes. Evidence from speech disorders includes complete closure of /s/ in functional articulation disorders (Hardcastle & Gibbon, 1997), hearing impairment (Schmidt, 2007), AOS (Bartle-Meyer et al., 2009) and traumatic brain injury (TBI) (Hartelius et al., 2005).

4.4.6 Lack of groove

This pattern is similar to *Wide Groove Alveolar* pattern but is concerned with a pattern of contact that shows lateral bracing on both sides of the palate but with no narrowing, therefore no real evidence of a narrowed tongue groove down the midline of the palate.

4.4.7 Anterior groove + velar constriction

This pattern is similar to *double articulation* but in place of complete alveolar contact there is an alveolar groove pattern produced alongside a velar constriction. This is not a commonly found pattern. Double articulations found in place of the typical alveolar sibilant pattern tend to be similar to the *Double articulation* pattern described in 4.3.6.

4.4.8 Affricate pattern

The affricate pattern is identified by a clear period of complete closure followed by an anterior grooved pattern. This pattern was identified in tandem with the auditory analysis, therefore identification was made when an affricate is heard (this is the only case where this happened). This affricate pattern is one that is seen during the production of typical post-alveolar affricates (/ʧ/ and /ʤ/). Affrication of sibilants is not a common misarticulation of /s/ or /ʃ/ but has been noted in the speech production of typically developing children (Dodd et al., 2002).

4.4.9 Velar constriction with lateral contact

This pattern describes a velar articulation with more contact in the palatal place of articulation. The patterns noted are similar in nature to palatal fricative articulations. Howard (2004) notes similar patterns to this in speakers with cleft palate with long standing speech errors (for target /s/ and /ʃ/).

4.4.10 Articulatory drift

Gibbon and Wood (2002) define articulatory drift as a plosive articulation that has a different placement at the release of closure to the placement at the initiation of the articulation. They analysed a group of children with articulation and phonological disorders who also used undifferentiated gestures and noted articulatory drift in a high percentage of their productions of /t/ and /d/. Articulatory drift has been also identified in children with cleft palate during the production of nasals and affricates (Howard, 2004).

4.5 /ʃ/ taxonomy and pattern discussion

The taxonomy for /ʃ/ production is presented below (Figure 4-4) with a description of each pattern as identified in these data, along with an example EPG pattern from the same data.

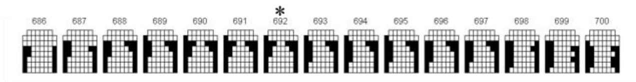
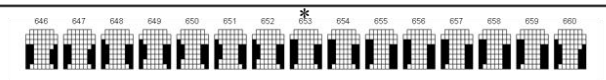
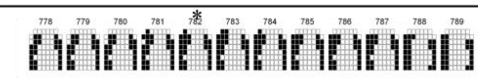
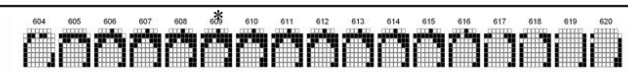
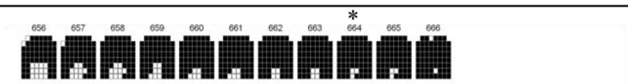
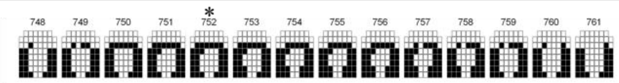
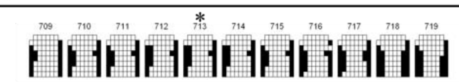
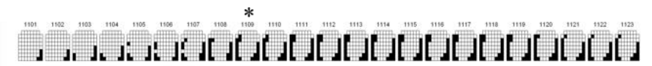
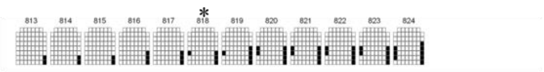
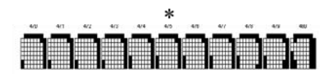
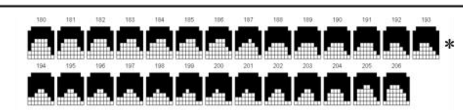
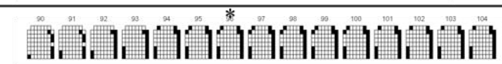
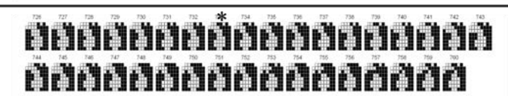
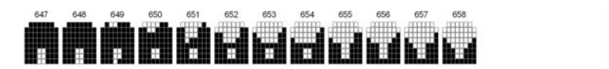
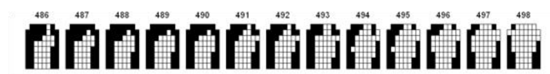
EPG Pattern Description	Example EPG pattern from annotated region
Typical post alveolar fricative: Narrowest groove at post-alveolar region (rows 3-4) with lateral bracing. May be asymmetrical	
Lack of groove: lateral bracing but no evidence of any narrowing	
Fronted groove: anterior groove with lateral bracing but at row 1 or 2	
Complete anterior closure: complete alveolar closure with lateral bracing	
Undifferentiated gesture: contact across palate as if tongue pushed up to palate with no evidence of separate control of tip/blade and body.	
Double articulation: evidence of discrete anterior closure with simultaneous discrete velar closure	
Wide groove: Narrowest part of groove 4 or more electrodes wide	
Velar constriction with lateral contact: evidence of velar closure with lateral contact	
Minimal contact: overall minimal tongue contact (with only contact at sides of palate)	
Anterior closure with lack of lateral seal: Complete closure at rows 1 or/and 2 with lack of complete lateral bracing	
Lateral fricative: Complete anterior closure from rows 1-3 (and possibly beyond) with lack of lateral seal at velar place of articulation	
Lack of lateral seal: Incomplete lateral bracing	
Anterior groove + velar constriction: presence of grooving with simultaneous velar closure	
Articulatory drift: change of P.O.A. during closure phase (e.g. complete alveolar closure to velar closure)	
Affricate pattern: clear evidence of period of complete closure followed by anterior groove	

Figure 4-4: Taxonomy for /ʃ/ pattern analysis. With description and example provided. * indicates specific example frame of described pattern type

4.5.1 Typical post-alveolar fricative pattern

This pattern is defined as the typical post-alveolar sibilant pattern as established from past research (Fletcher & Newman, 1991; Gibbon et al, 1996; Timmins et al, 2007).

The midline groove is at its narrowest at the post-alveolar region of the palate and there is lateral bracing (McLeod & Singh, 2008).

4.5.2 Fronted groove

The fronted groove pattern is the same as the typical alveolar sibilant pattern in 4.4.1 above.

4.5.3 Wide groove

This is another pattern reflecting the presence of a groove at the post- alveolar place of articulation but this time the groove is more than 3 electrodes wide. Groove width has been noted to be wider for post-alveolar sibilant than the alveolar sibilant so it may be that using the same definition for both sibilants was incorrect. The results will be discussed with this in mind.

4.5.4 Other /ʃ/ patterns

The other patterns in the /ʃ/ taxonomy are described previously with regard to the /t/ and /s/ target patterns.

4.6 Results

The above information was derived from an analysis of the DS speech data. The patterns were identified from a visual analysis of the annotated regions of the target sounds. The subsequent analysis using the above taxonomies was performed by the PhD researcher without any further reliability measures. It is noted that establishing the reliability of these taxonomies is required for further application of this categorisation technique. The results from the analysis of the data with reference to these patterns will be presented in Chapter Six.

4.7 Summary of Chapter

This chapter presented 3 new taxonomies (though a slightly different version of the /t/ taxonomy had been reported in Timmins et al. (2011)) for the visual analysis of disordered articulations of /t/, /s/ and /ʃ/. These taxonomies were created by visual examination of the articulation patterns produced by all the speakers in the experimental group (DS). The taxonomies were adapted as and when new articulation patterns were identified. Although based on data from the experimental group in this study, the same taxonomies will also be used to analyse the visual patterns of articulation from the TD group and the AD group.

5 Results part one - Perceptual and quantitative EPG measures

5.1 Introduction

The results will be presented across three chapters. The first will look at the perceptual and quantitative Electropalatography (EPG) analysis. The second results chapter will present results from the descriptive EPG analysis and the third and final results chapter will present data from 5 case studies.

This chapter will be structured in two sections: perceptual and articulatory analysis. Results will be presented in bar charts, box plot figures and tables. Box plots show the median value represented by a black horizontal line, IQR values (25 & 75%) by the height of the box, the range of values between highest and lowest by whiskers above and below the box. Outliers are represented by circles and stars.

The results are presented in order of methodology rather than research questions. The results presented in this following chapter will help to answer RQ1, RQ2 and RQ3:

> RQ1 – Do children with DS show more atypical articulation patterns in errors of sibilant production in comparison to TD and typical AD?
> RQ2 – Is there evidence of speech motor difficulties in children with DS as measured by spatial and temporal variability?
> RQ3 - Do children with DS present with atypical EPG measures and patterns for perceptually acceptable productions of sibilants?

Results from the perceptual analysis will be presented first. The measures below are provided to help answer RQ1, presented with relevant hypotheses:

- Down's syndrome (DS), typically developing children (TD) and typical adults (AD) percentage target consonant acceptable (PTA) results for target sounds (**H1**)
- DS and TD Phonetic Error (PE) results for target sounds (**H3**)
- DS and TD Error pattern results for target sounds (**H3**)

- Correlation of perceptual findings with age and standardised speech assessment scores (DEAP) (**H2**)

Results from the quantitative EPG measures will then follow. The measures below are provided to help answer RQ1, RQ2 and RQ3, presented with relevant hypotheses:

- DS, TD and AD Centre of Gravity (COG) results for target sounds (**RQ1, H4; RQ2: H8; RQ3, H13**)
- DS, TD and AD Whole Total Contact (WTM) results for target sounds (**RQ1, H5; RQ2: H8; RQ3, H13**)
- DS, TD and AD variability (Overall spatial variability (OSVar) and Perceptually acceptable spatial variability (PSVar)) results for target sounds (**RQ2, H9**)
- DS, TD and AD Temporal variability (COV) results for target sounds (**RQ2, H11**)
- DS and TD Canonical analysis (CA) results for target sibilants (**RQ1, H7**)

It is important to acknowledge the small Ns in the participant groups as this may influence results from the above measures. The total number of speakers and the overall number of repetitions of each target sound is presented in Table 5-1 for the three participant groups.

		/t/		/s/		/ʃ/	
	No. of speakers	Total no. of repetitions	% productions perceptually acceptable	Total no. of repetitions	% productions perceptually acceptable	Total no. of repetitions	% productions perceptually acceptable
DS	25	240	*71*	246	*61*	231	*44*
TD	10	98	*100*	100	*94*	99	*86*
AD	8	80	*100*	79	*100*	80	*100*

Table 5-1: Number of speakers and total number of repetitions alongside % productions perceptually acceptable for each participant group (DS: Down's syndrome; TD: Typically Developing; AD: Adult), and target sound (/t/, /s/ and /ʃ/).

5.2 Perceptual Analysis

The perceptual analysis provided PTA measures from the attempted productions for the target sounds /t/, /s/ and /ʃ/ from the three speaker groups AD, TD and DS, as transcribed by 3 different people. Table 5-3 (below) presents all attempted productions of the target sounds for all speakers with numbers of those perceived to be perceptually acceptable.

The group results for the PTA for the target consonants (Figure 5-1) show that, as may be expected, the AD group produce /s/, /ʃ/ and /t/ with 100% accuracy. The TD group produce /t/ with 100% accuracy. However, the target sibilants are produced with less accuracy: /s/ (mean: 94%, SD: 10) /ʃ/ (mean: 86%, SD: 28). For the DS group there are low levels of accuracy for all three target sounds and higher standard deviations: /t/ (mean: 70.5%, SD: 33.2), /s/ (mean: 61, SD: 34.8) and /ʃ/ (mean: 44.4, SD: 32.6). The pattern of difficulty is the same for the DS and the TD group (with /ʃ/ being the least acceptable target sound), but much greater difficulties are displayed by the DS group. There is a clear difference in spread across the three groups.

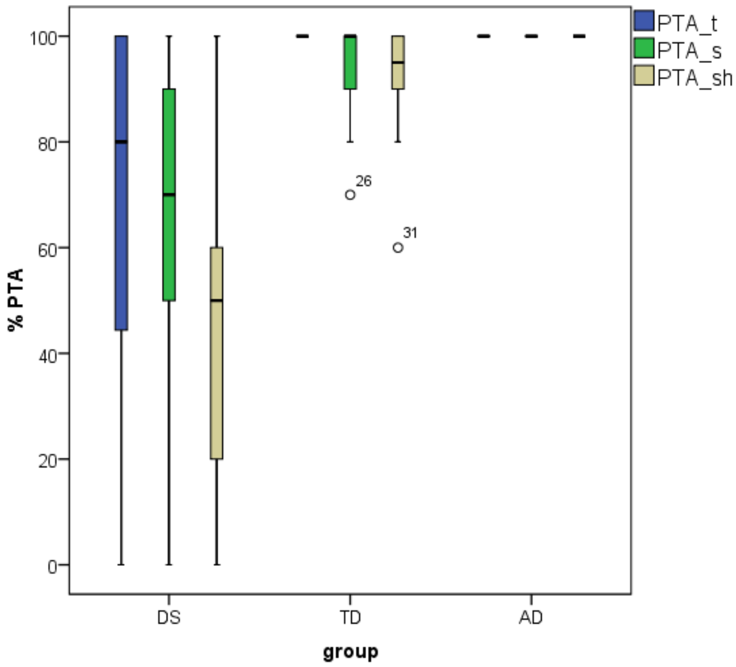


Figure 5-1: Boxplot showing median and IQR values of percentage target consonant acceptable (PTA) scores for target /t/, /s/ and /ʃ/ for DS, TD and AD groups.

Mann Whitney U tests identified significant differences between the DS and TD groups and DS and AD groups for all three target sounds (Table 5-2 below).

	PTA /t/	PTA /s/	PTA /ʃ/
DS vs TD	n = 25 (DS), 10 (TD) U = 50.00 p=.002	n = 25 (DS), 10 (TD) U = 45.00 p=.003	n = 25 (DS), 10 (TD) U = 21.50 p <.001
DS vs AD	n = 25 (DS), 8 (AD) U = 40.00 p=.006	n = 25 (DS), 8 (AD) U = 20.00 p=.001	n = 25 (DS), 8 (AD) U = 4.00 p <.001
TD vs AD	ns	ns	ns

Bonferroni corrected significance value p=0.0167
ns = not significant

Table 5-2: Results of Mann Whitney U tests for perceptually acceptable scores (PTA) for target sounds in DS, TD and AD groups.

5.2.1 DS PTA results

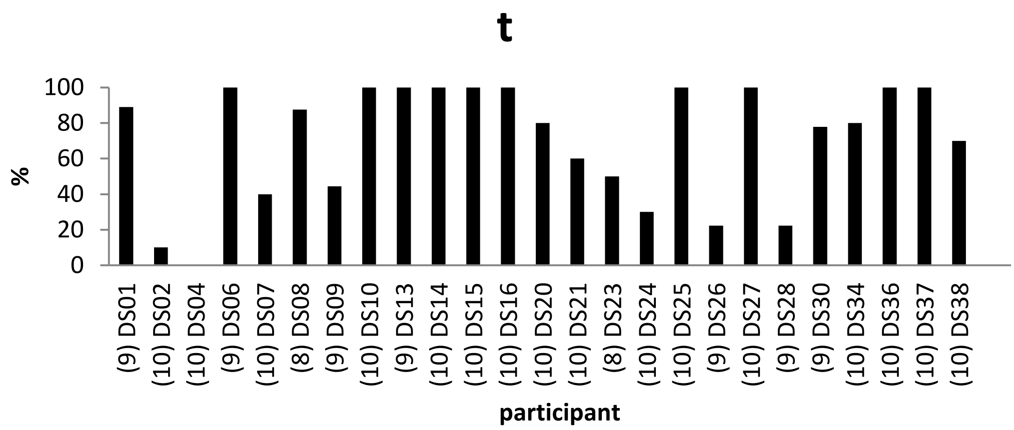


Figure 5-2: PTA (percent target consonant acceptable) scores for all participants with DS for target /t/ (total numbers of attempted productions in brackets)

There is considerable variation in the DS group for the production of /t/ (COV = 0.47). While the group result shows a moderately high level of PTA (70.5%), individual results show that 17 of 25 speakers produce target /t/ with more than 50% accuracy, but only DS04 has 0% PTA for /t/. In typical speech acquisition research a phoneme is considered acquired in some studies when it is produced correctly more than 75% of the time (McLeod & Bleile, 2003). With this in mind, 15 of the DS speaker group could be said to have acquired /t/.

	/t/ in 'toe'		/s/ in 'sun'		/ʃ/ in 'sheep'	
	reps	acceptable	reps	acceptable	reps	acceptable
DS01	9	*8*	10	*2*	10	*3*
DS02	10	*1*	10	*1*	10	*0*
DS04	10	*0*	10	*0*	0	*0*
DS06	9	*9*	10	*10*	10	*0*
DS07	10	*4*	10	*7*	10	*6*
DS08	8	*7*	9	*8*	10	*4*
DS09	10	*4*	10	*5*	9	*9*
DS10	10	*10*	10	*10*	10	*9*
DS13	9	*9*	10	*5*	9	*8*
DS14	10	*10*	10	*2*	10	*0*
DS15	10	*10*	10	*10*	10	*5*
DS16	10	*10*	10	*9*	10	*4*
DS20	10	*8*	10	*6*	10	*6*
DS21	10	*6*	10	*9*	10	*7*
DS23	8	*4*	6	*0*	10	*3*
DS24	10	*0*	10	*6*	10	*0*
DS25	10	*10*	10	*5*	10	*8*
DS26	9	*2*	10	*9*	10	*6*
DS27	10	*10*	10	*10*	10	*6*
DS28	9	*2*	10	*7*	10	*3*
DS30	9	*7*	10	*5*	9	*0*
DS34	10	*8*	10	*0*	10	*2*
DS36	10	*10*	10	*7*	10	*6*
DS37	10	*10*	10	*10*	10	*5*
DS38	10	*7*	10	*8*	10	*9*
Mean	9.5	*6.7*	9.7	*6.2*	9.3	*4.2*

	/t/ in 'toe'		/s/ in 'sun'		/ʃ/ in 'sheep'	
	reps	acceptable	reps	acceptable	reps	acceptable
TD04	10	*10*	10	*7*	10	*9*
TD24	10	*10*	10	*10*	9	*9*
TD25	10	*10*	10	*10*	10	*9*
TD26	10	*10*	10	*10*	10	*10*
TD27	10	*10*	10	*10*	10	*10*
TD28	10	*10*	10	*10*	10	*1*
TD29	9	*9*	10	*10*	10	*10*
TD31	10	*10*	10	*10*	10	*10*
TD32	10	*10*	10	*8*	10	*8*
TD33	9	*9*	10	*9*	10	*9*
Mean	9.8	*9.8*	10.0	*9.3*	9.9	*8.6*

	/t/ in 'toe'		/s/ in 'sun'		/ʃ/ in 'sheep'	
	reps	acceptable	reps	acceptable	reps	acceptable
AD01	10	*10*	10	*10*	10	*10*
AD02	10	*10*	10	*10*	10	*10*
AD03	10	*10*	10	*10*	10	*10*
AD04	10	*10*	10	*10*	10	*10*
AD05	10	*10*	10	*10*	10	*10*
AD06	10	*10*	10	*10*	10	*10*
AD07	10	*10*	10	*10*	10	*10*
AD08	10	*10*	9	*9*	10	*10*
Mean	10.0	*10.0*	9.9	*9.9*	10.0	*10.0*

Table 5-3: Number of productions of target consonants (repetitions) for all members of DS, TD and AD groups with number of acceptable productions in italics.

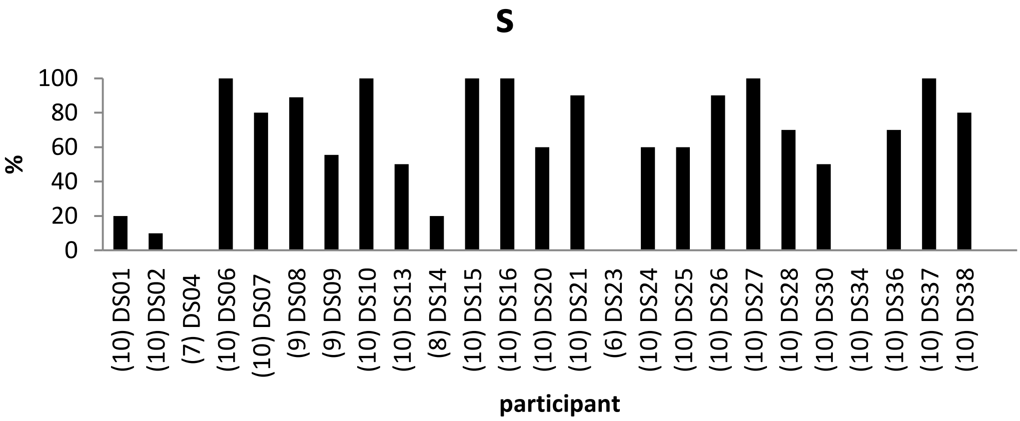


Figure 5-3: PTA (percent target consonant acceptable) score for all participants with DS for target /s/ (total numbers of attempted productions in brackets)

The lower PTA for /s/ in the DS group is explained more clearly by Figure 5-3**.** Three speakers show no acceptable productions of target /s/, though seven speakers produce target /s/ with no errors. Again, the results vary across the group (COV=0.57). Only 10 of the 25 participants present with a PTA score of 75% for target /s/.

The individual results for target /ʃ/ in the DS group (Figure 5-4 below) show a much lower level of PTA than the other 2 consonants /t/ and /s/ and a higher level of between-speaker variability (COV: /t/ = 0.47, /s/ = 0.57 and /ʃ/ =0.73). Six participants produced all tokens as errors, and only five produced 75% or more correctly.

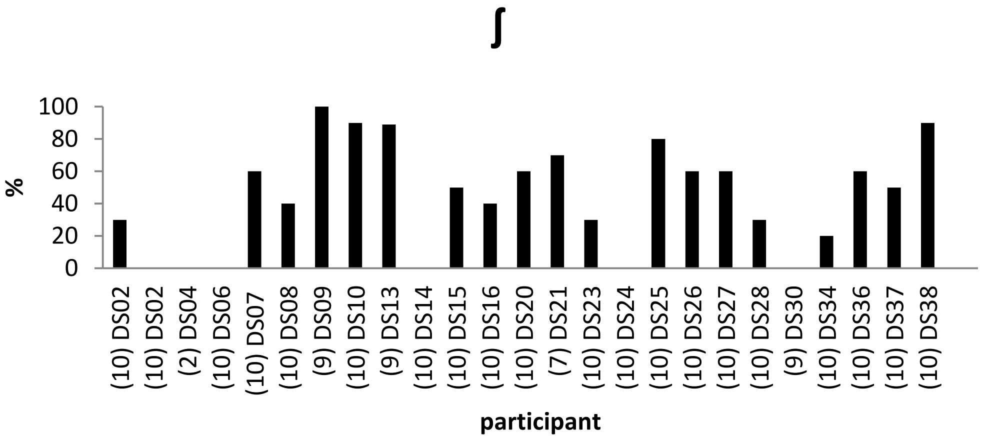


Figure 5-4: PTA (percent target consonant acceptable) score for all participants with DS for target /ʃ/ (total numbers for attempted productions in brackets)

5.2.1.1 Relationship between PTA scores for target sounds and age: DS

All DS PTA scores were correlated (using Spearman's Rho) with each other, chronological age and DEAP PCC in order to investigate whether participants with low scores on individual target sounds were poorer across all sounds and whether these low scores were reflected in a standardised speech assessment score (DEAP) and linked to age. As seen in Table 5-4 there were no significant correlations between the PTA scores and chronological age in the DS group. Only PTA /t/ correlates significantly with the DEAP PCC scores, suggesting that only ability to produce /t/ is related to overall consonant production ability.

	CA	PTA /t/	PTA /s/	PTA /ʃ/
PTA /t/	ns			
PTA /s/	ns	r=.409, p=.042		
PTA /ʃ/	ns	ns	ns	
DEAP PCC	ns	r=.524, p=.007	ns	ns

N=25; grey-shading highlights significant relationships

ns = not significant

Table 5-4: Spearman's Rho correlations for DS group. CA: Chronological Age; PTA: perceptually acceptable target score; DEAP PCC: percent consonants correct score from Diagnostic Evaluation of Articulation and Phonology (Dodd et al, 2002)

5.2.2 TD PTA results

The TD group produced target /t/ with 100% accuracy so the individual results will not be presented.

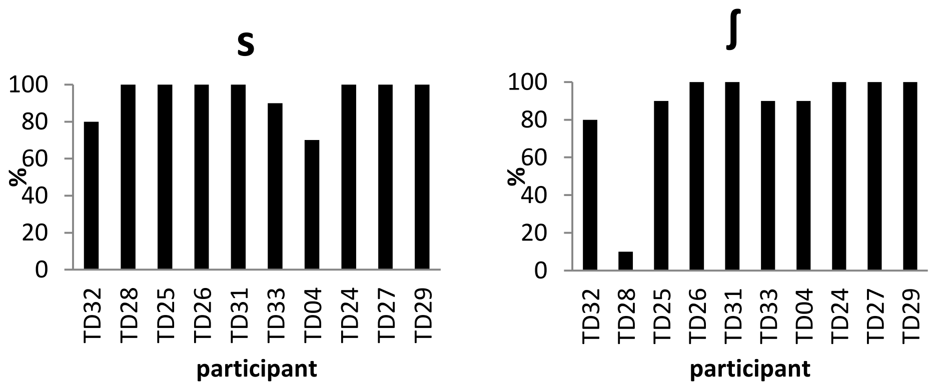


Figure 5-5: PTA (%) scores for all TD speakers for target /s/ and /ʃ/, arranged by age (youngest to the left)

The TD results for /s/ and /ʃ/ are presented in Figure 5-5: PTA (%) scores for all TD speakers for target /s/ and /ʃ/, arranged by age (youngest to the left) in order of increasing age, to reflect the ongoing phonological development in the younger ages of the control group. The TD group show less between-speaker variability for /s/ than the DS group (COV: DS= 0.57, TD=0.11). TD32 (aged 3;8) is the youngest and does not produce a consistently acceptable /s/ throughout the repetition data. However, older speakers also show errors. For example, TD33 and TD04 do not produce an acceptable /s/ 100% of the time (both 6;4 at the time of recording). The overall production for /ʃ/ presents more errors than target /s/, but with less variation across the group than in the DS group (COV: DS=0.74, TD=0.32). TD28 only produces one acceptable token of target /ʃ/. TD33 and TD04 again show lower levels of PTA compared to controls of the same age but comparable to the youngest control subjects.

5.2.2.1 Relationship between PTA scores for target sounds and age: TD

All TD PTA scores were correlated (using Spearman's Rho) with each other, chronological age and DEAP PCC in order to investigate whether participants with low scores on individual target sounds were poorer across all sounds, and whether these low scores were reflected in a standardised speech assessment PCC score (DEAP), and linked to age.

	CA	PTA /s/	PTA /ʃ/
PTA /s/	r=.188, p=.604		
PTA /ʃ/	r=.706, p=.023	r=.524, p=.120	
DEAP PCC	r=.492, p=.148	r=.301, p=.398	r=.618, p=.057

N=10; grey-shading highlights significant relationships

Table 5-5: Spearman's Rho correlations for TD group. CA: Chronological Age; PTA: perceptually acceptable target score; DEAP PCC: percent consonants correct score from Diagnostic Evaluation of Articulation and Phonology (Dodd et al, 2002)

As shown in Table 5-5, there was a significant correlation between the PTA /ʃ/ score and chronological age in the TD group. Neither of the sibilants shows a relationship with the DEAP PCC, or each other.

5.2.3 Phonetic error scores (PE)

The phonetic error scores present a percentage of acceptable use of the following features: place of articulation, manner of articulation and voicing. These scores were calculated from the perceptual analysis for each target sound for each individual speaker. Group results from the analysis of target /s/ for the DS and TD groups are presented below.

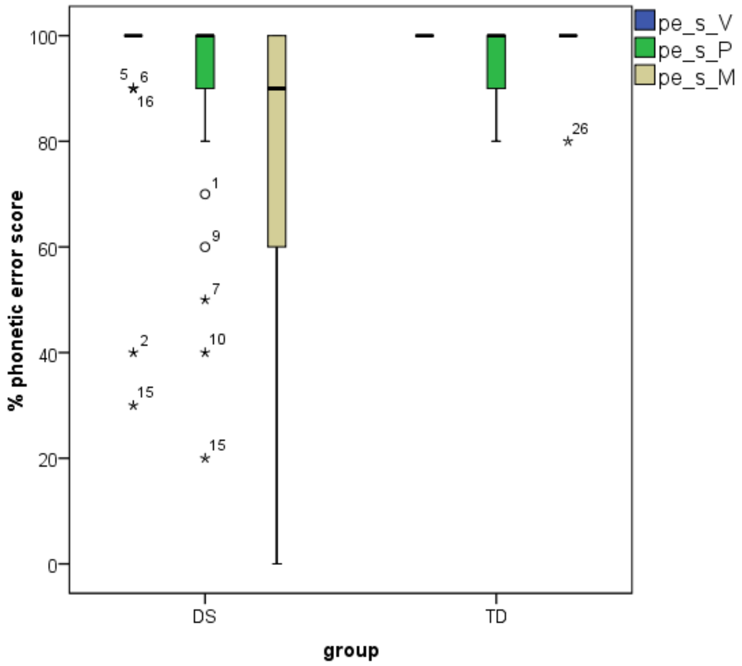


Figure 5-6: Boxplot showing median and IQR values of percentage of features correct (PE score) for target /s/ for DS and TD speaker groups. V: voicing, P: place of articulation, M: Manner of articulation.

In Figure 5-6 both the DS and TD groups show more success in maintaining the acceptable voicing (DS: mean=94%, SD=18; TD mean=100%) during their productions of target /s/. The errors in the DS group occur most often with manner of articulation, with 73% (SD=32.1) of the productions perceived as having the acceptable manner. Place of articulation presented with some errors (mean: 88%, SD: 22.2). This pattern is not reflected in the results from the TD group who are more successful in manner (mean=98%, SD=6.3) than place of articulation (mean: 96%, SD: 6.9).

Figure 5-7 presents the results of the PE analysis for target /ʃ/ in the DS and TD groups. Both groups show a similar pattern of errors with place of articulation being the most affected followed by manner of articulation. Place of articulation success is low for the DS group (mean: 58%, SD: 33.8), compared to the TD group (mean: 88%, SD: 27.9) and the scores for target /s/. Manner of articulation is less successful in the DS group than the TD group (DS: mean=80%, SD=30.1; TD: mean=98%, SD=4.21). The voicing for target /ʃ/ is the most successful feature for both groups (DS: mean=90%, SD=26.5; TD: mean=100%).

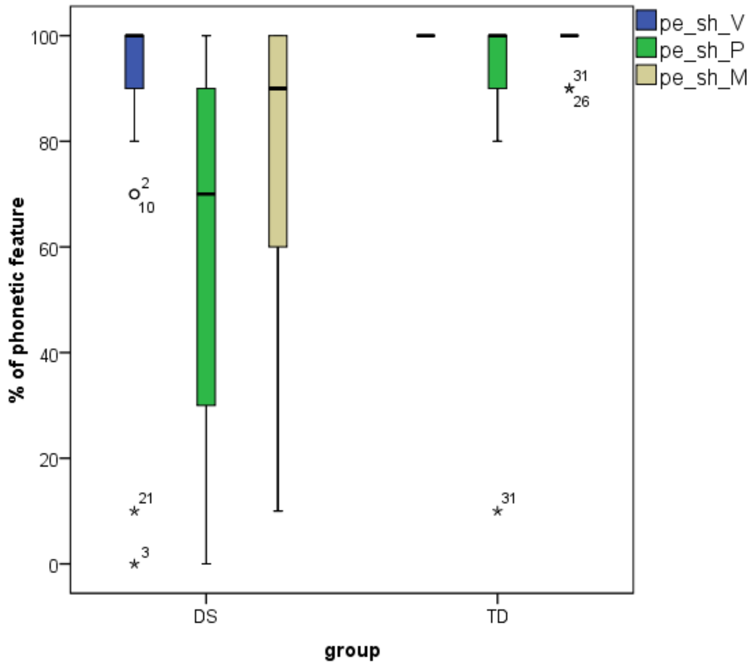


Figure 5-7: Boxplot showing median and IQR values for percentage of features correct (PE) for target /ʃ/ for DS and TD speaker groups. P: place of articulation, M: Manner of articulation, V: voicing

5.2.4 Perceptual error pattern analysis

The attempted productions of /s/ and /ʃ/ were subjected to a perceptual error pattern analysis for the DS and the TD speakers. The percentage of typical patterns and atypical patterns (as defined in Table 3-4) of /s/ errors for both groups are presented in Figure 5-8 below. The numbers of errors for the TD group were small (6 errors in total, produced by only three speakers).

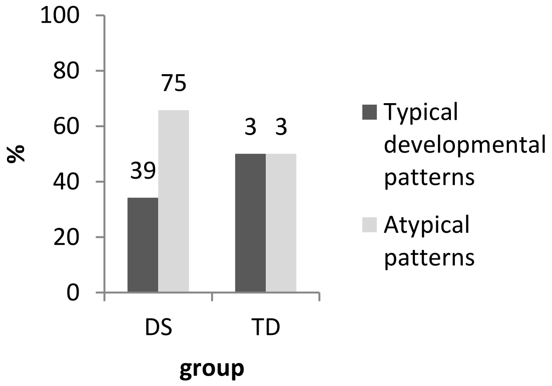


Figure 5-8: Percentage of developmental and atypical error patterns identified in DS and TD speakers for /s/ errors, with raw numbers of pattern types on chart

Stopping of the sibilant to [t] was the only developmental error pattern identified (noted twice for TD04 and once for TD33). The other 3 errors were considered to be atypical and were the result of *backing* (producing target /s/ as [ʃ] which occurred twice for TD32) and *dentalisation* (used once by TD04). The DS group show a much higher number of errors and atypical patterns (80%) than the TD group. A total of 114 errors and 11 different error patterns were identified for the attempted productions of /s/ in the DS group. Figure 5-9 below presents the number of each pattern identified.

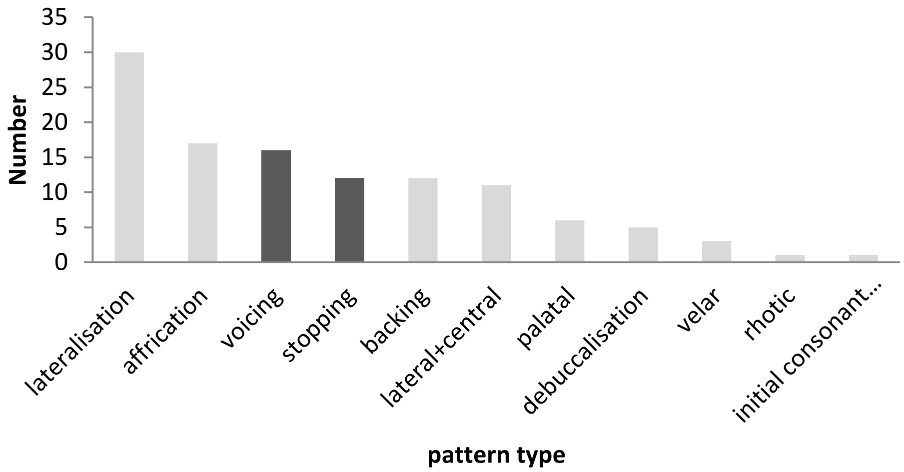


Figure 5-9: Number of error patterns identified for production of /s/ in the DS group. Dark bars are typical patterns, light bars are atypical patterns

The most common error type identified in the DS data was lateral articulation of /s/. The typical error patterns identified were *voicing* and *stopping.* Atypical patterns included *backing*, *lateral+central* and *palatal* substitutions.

The percentage of typical and atypical patterns used in /ʃ/ production are presented in Figure 5-10 below. Again, the numbers of TD errors were small. There were 13 errors in total (from 5 different speakers), these included *affrication* and *palatal* errors but the most common error pattern was *fronting.* The DS group produced a total of 10 different error patterns.

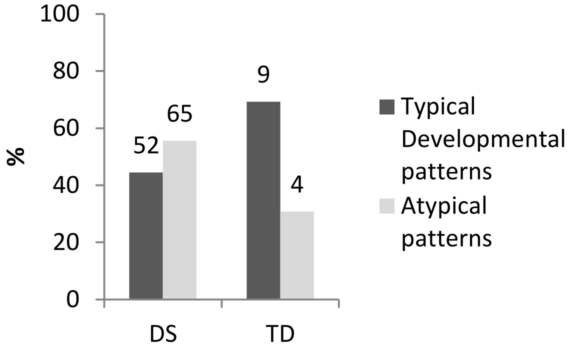


Figure 5-10: Percentage of developmental and atypical error patterns identified in DS and TD speakers for/ʃ/ errors, with raw numbers of patterns on chart

Analysis of the DS data found that some of the errors could not be classified (this amounted to 16 errors, 13% of errors for /ʃ/). There are high levels of the typical error pattern of *fronting* (target /ʃ/ produced as [s]) but the DS group also show many other atypical error types with high numbers of substitutions identified as *lateral, affricate* and *palatal* consonants, and *debuccalisation* (Figure 5-11).

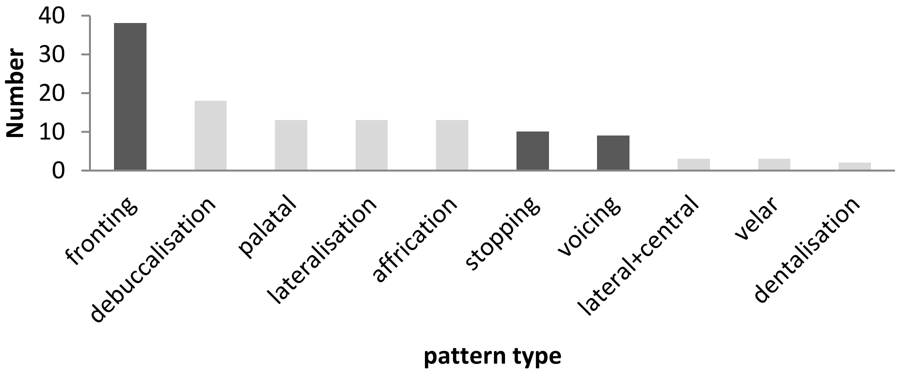


Figure 5-11: Number of error patterns identified for production of /ʃ/ in the DS group. Dark bars are typical error patterns, light bars are atypical error patterns

5.2.5 Relationship between perceptual error patterns for target sounds and age: TD and DS groups

Spearman's Rho correlations were run to assess the relationship between the use of error patterns and age in both the TD and DS group. It was expected that the TD group would show a decrease of the typical error patterns of *stopping* of /s/ and *fronting* of /ʃ/ as these substitutions are part of typical speech development. As expected correlation scores show that the TD group have a significant negative relationship with age and *stopping*, suggesting that *stopping* occurs less in the older children (N=10, r=-.803, p=.005). No similar relationship exists for *fronting*. No significant correlations were identified for the DS group.

5.3 Articulatory (EPG) measurements

The following section presents the results from all measurements of the data performed using specific EPG indices. These will include the spatial measurement, temporal measurement and canonical analysis results.

5.3.1 Spatial measurement: Centre of Gravity (COG)

The COG measure provides a score (between 0-8) that relates to the placement of electrodes contacted. An anterior articulation will have a high COG score and a posterior articulation will have a low score. Of the three target sounds, /t/ and /s/ typically present with high scores relating to production at the alveolar region of the palate. However /t/ may present with a higher score due to increased lingual-palatal contact as a result of complete alveolar closure. As a more retracted sound, target /ʃ/ would typically show a lower score than /t/ and /s/. Figure 5-12 below presents the COG scores for target /t/, /s/ and /ʃ/ for the three groups DS, TD, and AD.

As shown in Figure 5-12, /ʃ/ has a lower median COG score than /t/ and /s/ in all three speaker groups, and a larger spread of scores. The TD and AD groups show similar COG scores for /t/ and /s/ (/t/ mean scores: TD = 4.85; AD = 4.87, /s/ mean scores: TD = 4.55; AD = 4.62) but the DS group shows lower mean COG scores than the control groups (/t/ = 4.21; /s/ = 4.07).

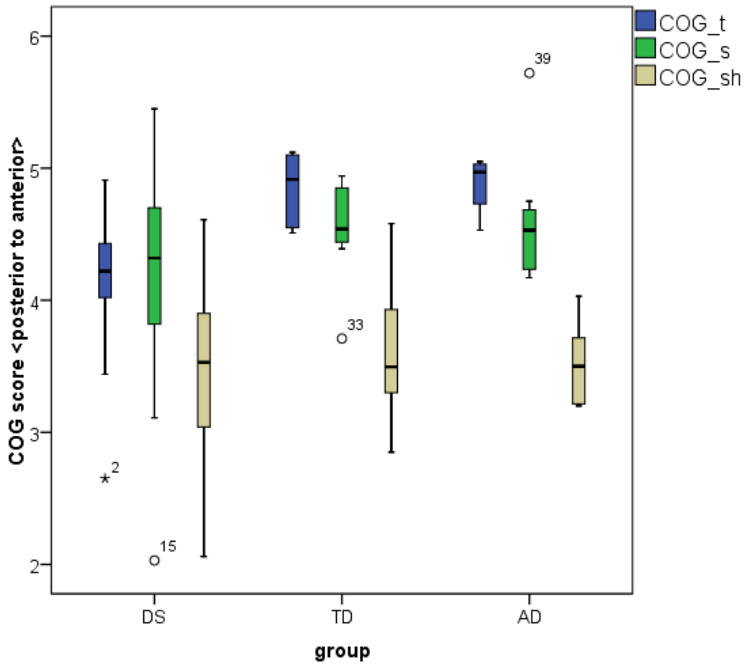


Figure 5-12: Boxplot showing median and IQR values of COG (centre of gravity) scores for DS, TD and AD groups for target /t/, /s/ and /ʃ/. A low score reflects a more posterior articulation and a high score reflects a more anterior articulation

As shown in Table 5-6 below, Mann Whitney U tests results suggest that the only significant group differences in the COG measures were for target /t/ for the DS group versus TD and AD /t/ COG scores. There were no significant scores for the sibilants.

	COG /t/	COG /s/	COG /ʃ/
DS vs TD	n = 25 (DS), 10 (TD) U = 15.00 p< .001	ns	ns
DS vs AD	n = 25 (DS), 8 (AD) U = 8.00 p< .001	ns	ns
TD vs AD	ns	ns	ns

Bonferroni corrected significance value p=0.0167
ns = not significant

Table 5-6: Results of Mann Whitney U tests for COG (centre of gravity) scores for target sounds in DS, TD and AD groups.

5.3.1.1 COG within-speaker variability

To assess within-speaker variability across the groups for COG measures, a coefficient of variation (COV) score was calculated for each speaker group for the COG measurements of all productions of /t/, /s/ and /ʃ/. The median and IQR values for group results of each target sound are presented in Figure 5-13 below. For all target sounds, individuals with DS show a higher COV than the other 2 groups, with a wider spread and outliers at the higher scores. The TD group show higher levels of variability than the AD group for all target sounds. There is no significant difference between the COV scores.

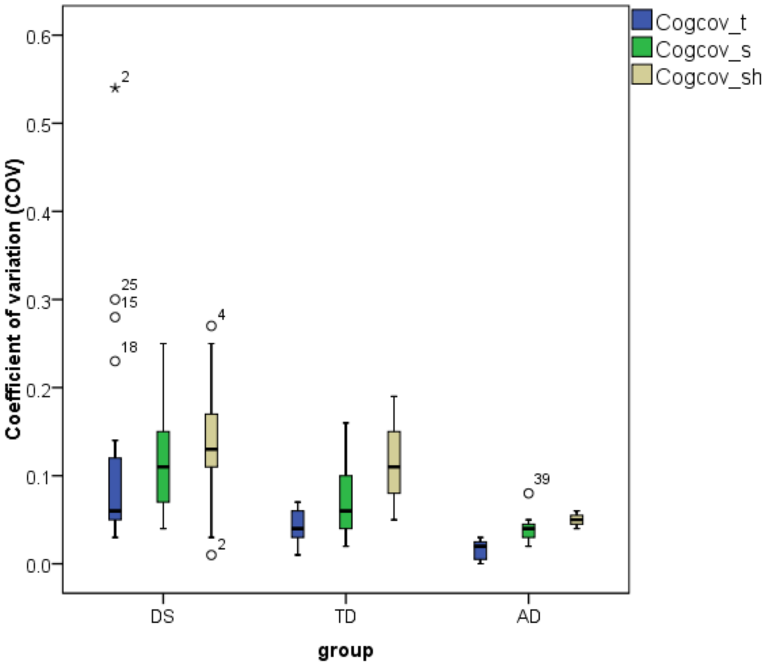


Figure 5-13: Boxplot showing median and IQR values for within-speaker variability (COV) of COG measures for target /t/, /s/ and /ʃ/ for DS, TD and AD speakers

Gibbon and Lee (2011) note that between-speaker comparison of COG means is not particularly because of individual speaker variability. Therefore Figure 5-14 shows individual COG scores for /s/ and /ʃ/ for DS, TD and AD groups. The majority of speakers in all groups show a tendency for a more anterior position for /s/ than /ʃ/. There is between-speaker variability for /s/ COG scores in the AD group (as noted for typical adults in Gibbon and Lee, (2011)) but all speakers show a difference in COG for /s/ and /ʃ/ in the expected direction. The majority of the TD group show a similar pattern to the AD group (except for 2 TD speakers who were at the younger end of the age range and were still producing errors for target /ʃ/ production). The DS group show a less similar pattern with most speakers showing the anterior positioning of /s/, however three of the DS group present with similar COG scores for the sibilants and three others show higher COG scores for /ʃ/ than /s/. Of the reversed COG relationships DS23 and DS30 present with very similar scores for the target sounds, however the COG scores for DS14 show a larger difference (/s/: mean=3.11, SD=0.79; /ʃ/: mean=3.83, SD=0.71).

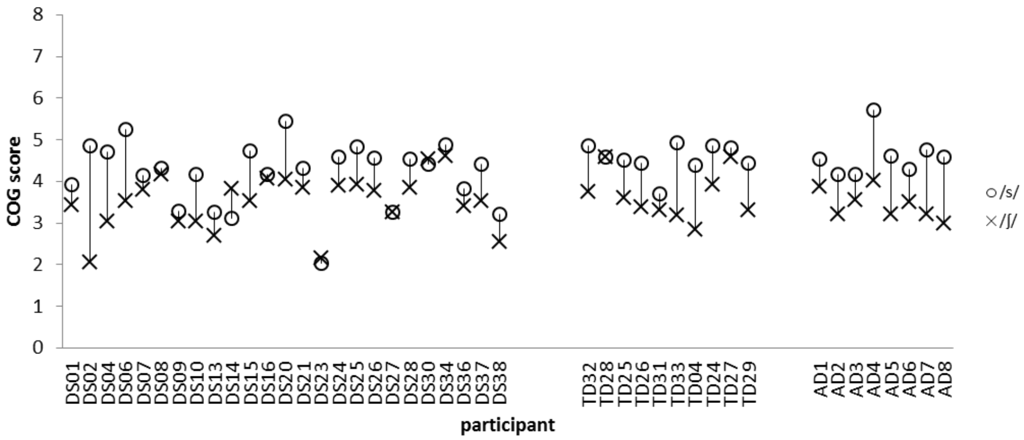


Figure 5-14: Individual speakers' mean COG (centre of gravity) scores for /s/ (o) and /ʃ/ (x) for all DS, TD and AD, with TD speakers presented from youngest to oldest. High scores show anterior articulation. No score indicates no measureable tokens were produced.

Figure 5-15 presents the group means of the COG score differences for all attempted productions of target /s/ and /ʃ/.

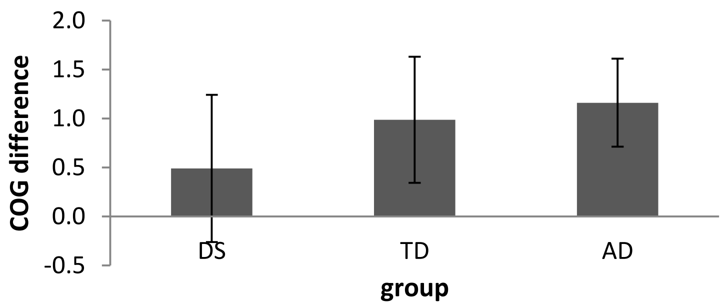


Figure 5-15: Mean and standard deviations for COG (centre of gravity) difference of /s/ and /ʃ/ for DS, TD and AD groups

The AD group show a large mean difference between the COG scores for /s/ and /ʃ/ and this difference decreases in the TD group, and further still in the DS group.

Although this suggests a tendency for less /s/ ~ /ʃ/ distinction in the speakers with DS, the group means were not significantly different.

5.3.1.2 Perceptually acceptable COG

The COG scores of perceptually acceptable productions for each speaker group are presented in Figure 5-16 below. Figure 5-17 shows the group mean COG difference scores.

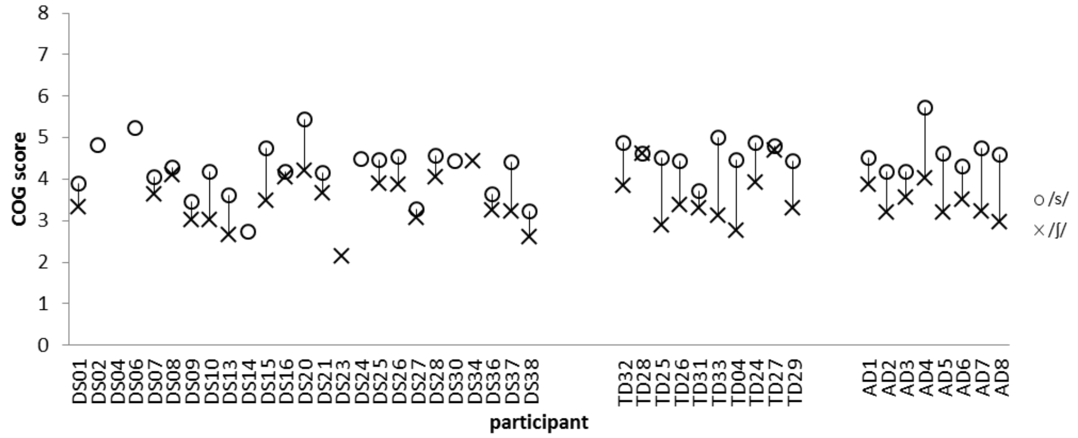


Figure 5-16: Individual speakers' mean COG (centre of gravity) scores for /s/ (o) and /ʃ/ (x), perceptually acceptable targets only, for all DS, TD and AD, with TD speakers presented from youngest to oldest. High scores show anterior articulation. No score indicates no measureable tokens were produced.

The perceptually acceptable COG scores show that, as expected, the adults retain the /s/~/ʃ/ distinction. The TD speakers also present with COG score distinctions for the target sibilants except for TD27 and TD28. These scores may be explained by motor equivalence strategies, where an anterior tongue position is perceived as an acceptable /ʃ/ due to increased lip protrusion. DS08 and DS16 maintain similar COG scores for /s/ and /ʃ/. However, DS23 and DS30 no longer present with comparable /s/ and /ʃ/ scores.

Removal of the perceptual errors (Figure 5-17) still finds that the group with DS show a smaller distinction between COG values for perceptually acceptable /s/ compared to /ʃ/ (this gap increases when comparing with TD then AD groups) suggesting that articulation patterns for perceptually acceptable tokens of the target sibilants are more similar to each other for the DS group. Mann Whitney U tests found a significant difference between the DS and AD group (U=21.5, p=.005), suggesting that children with DS have less articulatory distance between /s/ and /ʃ/ than typical adults, but not with typical children.

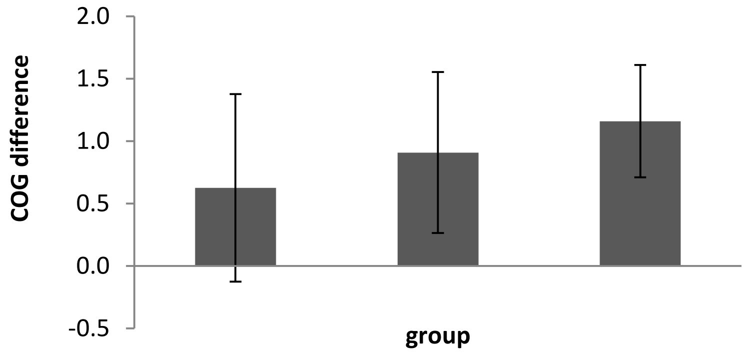


Figure 5-17: Mean and standard deviations for COG score difference of /s/ and /ʃ/ for DS, TD and AD groups, perceptually acceptable tokens only

5.3.1.3 Relationship between COG measures of target sounds and age: TD and DS groups

As the common error pattern for sibilant production is fronting of /ʃ/ to [s] and stopping of /s/ to [t], correlations were run on the COG scores for the sibilants and chronological age to investigate whether the participants were following a typical developmental pattern. There was a significant negative relationship for /ʃ/ COG scores (see Table 5-7 below) and chronological age when errors are also measured, suggesting that the articulation of /ʃ/ are more posterior in the older speakers. However, this relationship does not remain when only the perceptually acceptable tokens which may be due to the low numbers of perceptually acceptable tokens. There are no significant relationships for the TD group.

	COG /t/	COG /s/	COG /ʃ/	COG_corr /t/	COG_corr /s/	COG_corr /ʃ/
DS Age	ns	ns	r=-.423, p=.035	ns	ns	ns
TD Age	ns	ns	ns	ns	ns	ns

DS: N=25, TD: N=10; grey-shading highlights significant relationships
ns = not significant

Table 5-7: Spearman's Rho correlations for DS and TD chronological age and COG for target sounds. COG: centre of gravity; COG_corr: COG scores for perceptually acceptable tokens only

5.3.2 Spatial measurement: Whole total contact measure (WTM)

The whole total contact measure was calculated in order to assess whether children with DS present with increased lingual palatal contact in the articulation of sibilants (as noted in Hamilton, 1993) than typical children. The measure was calculated for all attempts at the target sounds and the perceptually acceptable tokens. Median and IQR values for each sound for each group are presented below in Figure 5-18. A score of 1 reflects complete lingual contact with the palate.

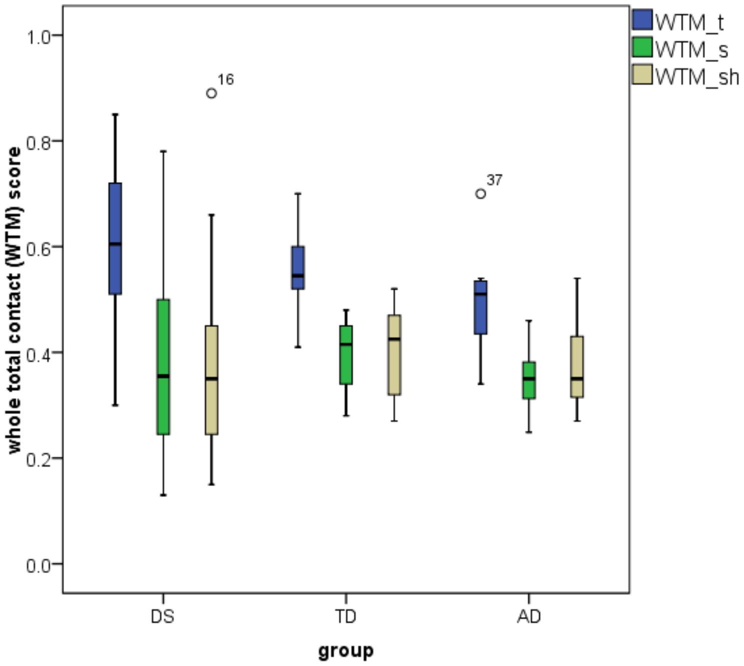


Figure 5-18: Boxplot showing median and IQR values of WTM (whole total contact measure) scores for DS, TD and AD groups for target /t/, /s/ and /ʃ/. A high score reflects high lingual-palatal contact (with 1 representing full palate contact).

The WTM scores in Figure 5-18 above for the three groups for /t/, /s/ and /ʃ/ shows that all three groups show increased lingual palatal contact for /t/ but show similar patterns for the sibilants. The DS group present marginally higher mean scores for /t/ (0.62) than the TD group (0.55) and the AD group (0.50). For the sibilant sounds there is no similar pattern to the /t/ productions. However both sibilants show slightly higher WTM scores for the TD (/s/: mean = 0.39, SD=0.07; /ʃ/: mean = 0.41, SD=0.09) group in comparison to the DS (/s/: mean = 0.40, SD=0.17; /ʃ/: mean= 0.38, SD=0.18) and AD (/s/: mean = 0.36, SD=0.07; /ʃ/ mean =

0.39, SD=0.09) groups. Mann Whitney U tests found no significant differences between groups for the three target sounds.

The individual results are presented below for each target sound. Figure 5-19 presents the WTM scores for the production of all tokens of target /t/ from the DS, TD and AD groups.

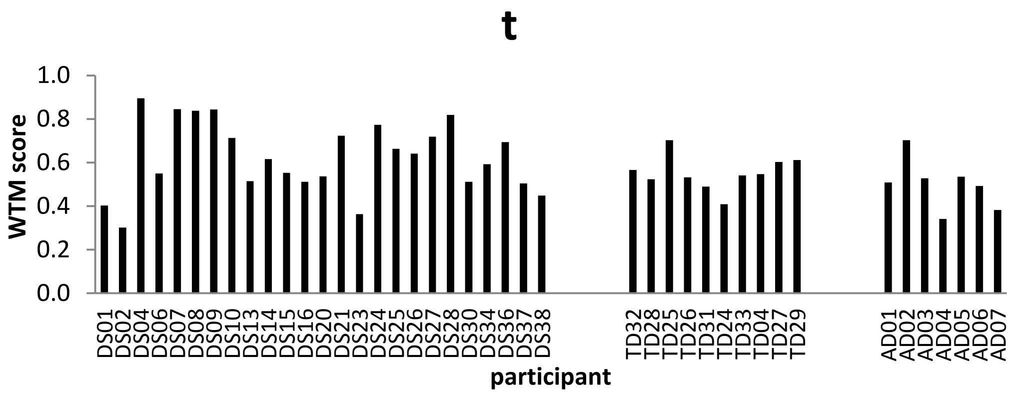


Figure 5-19: Individual mean WTM (whole total contact measure) scores for all speakers (DS, TD and AD) for /t/ production, TD participants presented in order of age (increasing). 0 = no lingual-palatal contact, 1= full lingual-palatal contact.

There is a wide range of lingual palatal contact for target /t/. Some speakers in the DS group show very high scores for WTM, with a few speakers presented low scores (ranging from 0.3 to 0.9). The TD group present a more consistent pattern with a smaller range of scores (0.4 to 0.7). The pattern of variability across groups is presented by the use of COV scores which reflect high levels of between-speaker variability in the DS group (DS = 0.26, TD = 0.14 and AD = 0.23).

Figure 5-20 presents the individual results for WTM for all speakers for target /s/. The AD and TD groups present a similar pattern with both groups ranging from 0.3 and 0.5. The DS group has a wider range of contact from DS23 at the very low scores (0.1), to DS30 at 0.7. There is no evidence of a consistent pattern of lingual-palatal contact for /s/ production. Between-speaker COV scores for target /s/ were DS = 0.44, TD = 0.17, and AD = 0.19.

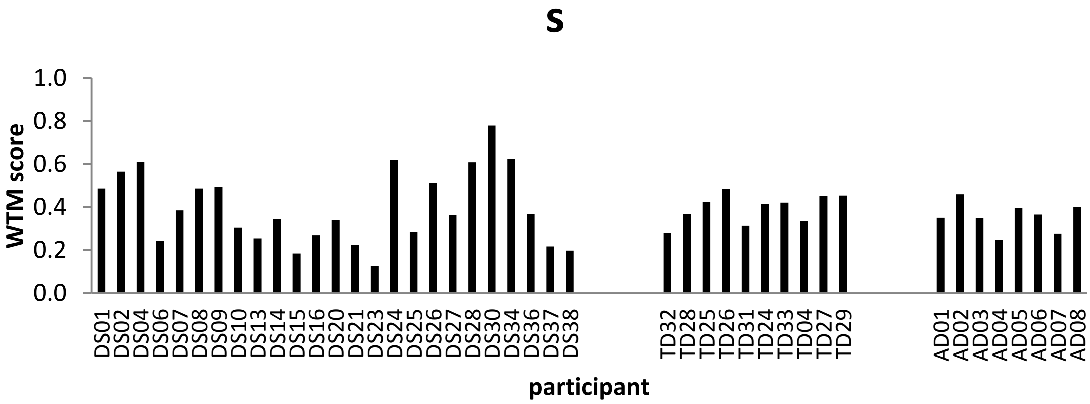


Figure 5-20: Individual WTM (whole total contact measure) scores for all speakers (DS, TD and AD) for /s/ production, TD participants presented in order of age (increasing). 0 = no lingual-palatal contact, 1= full lingual-palatal contact.

A similar pattern is presented in Figure 5-21 below for target /ʃ/ productions. The TD and AD groups have a small range of scores (0.3-0.5) but the DS group present a wider range (0.05–0.9). The DS group shows less uniformity in amount of lingual-palatal contact compared to the control groups. Between-speaker COV scores for target /ʃ/ were DS = 0.47, TD = 0.22 and AD = 0.23.

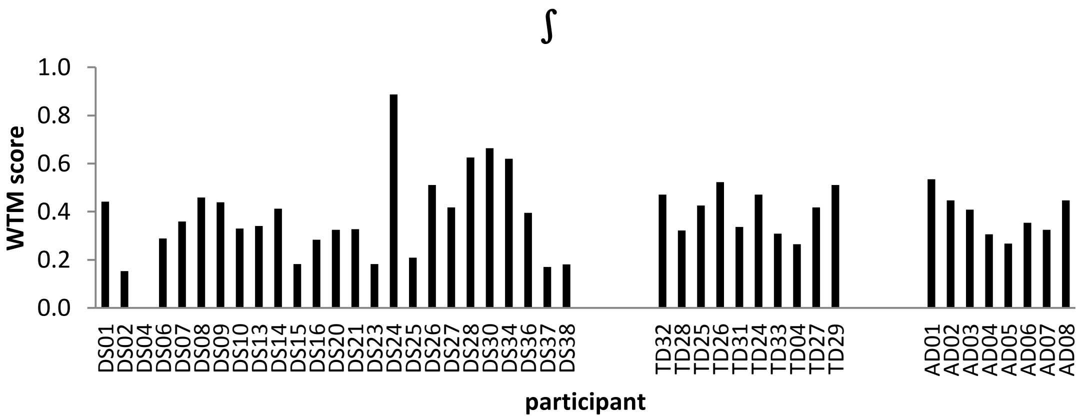


Figure 5-21: Individual WTM (whole total contact measure) scores for target /ʃ/ for DS, TD and AD groups), TD participants presented in order of age (increasing). 0 = no lingual-palatal contact, 1= full lingual-palatal contact.

5.3.2.1 WTM within-speaker variability

To assess within-speaker variability across the groups for WTM measures, a coefficient of variation (COV) score was calculated for each speaker for the WTM measurements of all productions of /t/, /s/ and /ʃ/. The median and IQR group results for each target sound are presented in Figure 5-22 below. For all sounds, the DS group show significantly higher COV scores (Table 5-8) than the TD groups, with a wider spread and outliers at the higher scores. The TD group show significantly higher levels of variability than the AD group for all target sounds.

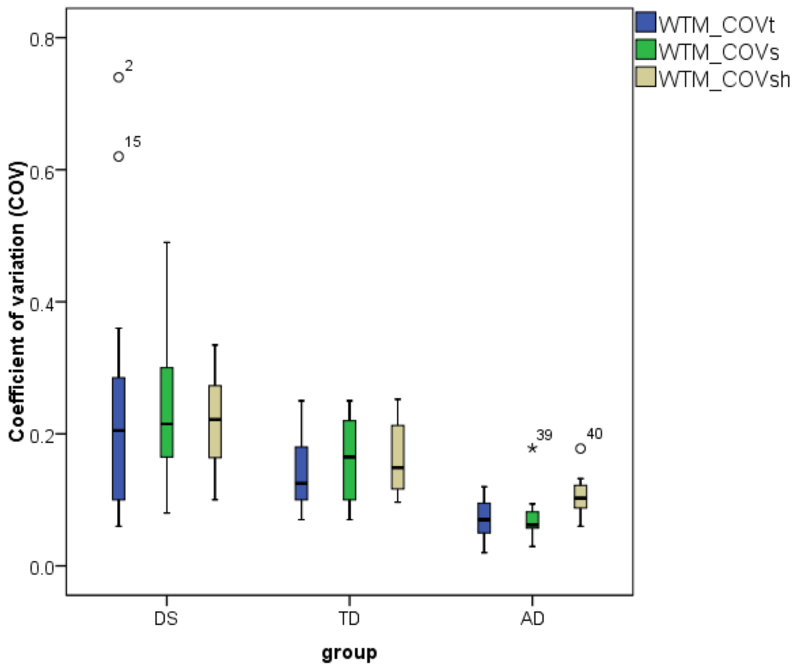


Figure 5-22: Boxplot showing median and IQR values for within-speaker variability (COV) of WTM measures for target /t/, /s/ and /ʃ/ for DS, TD and AD speakers

	WTM COV /t/	WTM COV /s/	WTM COV /ʃ/
DS vs TD	ns	ns	ns
DS vs AD	n = 25 (DS), 8(AD) U = 22.50 p=.003	n = 25 (DS), 8 (AD) U = 9.50 p<.001	n = 25 (DS), 8 (AD) U = 12.00 p <.001
TD vs AD	n = 10 (TD), 8 (AD) U = 10.00 p=.014	n = 10 (TD), 8 (AD) U = 9.00 p=.006	n = 10 (TD), 8 (AD) U = 13.00 p=.016

Bonferroni corrected significance value p=0.0167
ns = not significant

Table 5-8: Results of Mann Whitney U tests for WTM (whole total contact measure) COV scores for target sounds in DS, TD and AD groups.

5.3.2.2 Perceptually acceptable WTM

The WTM was calculated for all perceptually acceptable tokens of target /t/, /s/ and /ʃ/ for all three speaker groups. The WTM scores in Figure 5-23 show little differences to the overall WTM measures (Figure 5-19). However, the DS group still show higher levels of lingual-palatal contact for /t/ than the other speaker groups, and all groups have more lingual-palatal contact for /t/ than the target sibilants. While we may expect that acceptable productions of consonants may be produced in a similar manner whoever the speaker, the increased contact for target /t/ in the DS group suggests that children with DS produce target plosives with more lingual palatal contact even in perceptually acceptable productions. The sibilants behave differently with the DS group showing lower levels of lingual-palatal contact for acceptable productions. The nature of articulation patterns used for perceptually acceptable productions of the target sounds will be investigated further in Chapter 6.

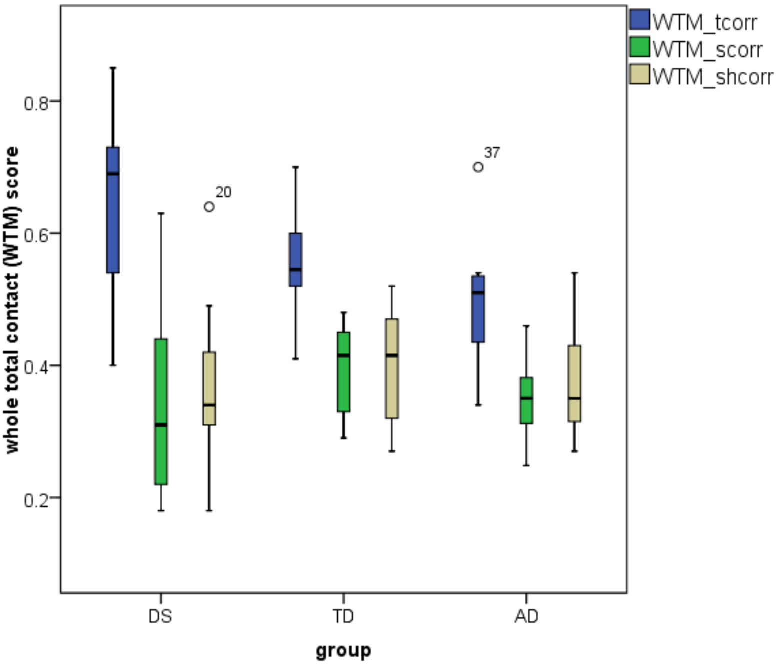


Figure 5-23: Boxplot showing median and IQR values of WTM scores for perceptually acceptable tokens (WTM_corr) of target /t/, /s/ and /ʃ/ for all three speaker groups (DS, TD and AD)

Figure 5-24 below presents the individual WTM scores for /t/ productions for all speaker groups. The results for perceptually acceptable /t/ show that there is variability across the speakers in the DS group. There is also variability in the TD (ranging from 0.4 to 0.7) and AD (ranging from 0.35 to 0.7) groups. The between-speaker COV scores for perceptually acceptable target /t/ were DS = 0.19, TD = 0.14, and AD = 0.23).

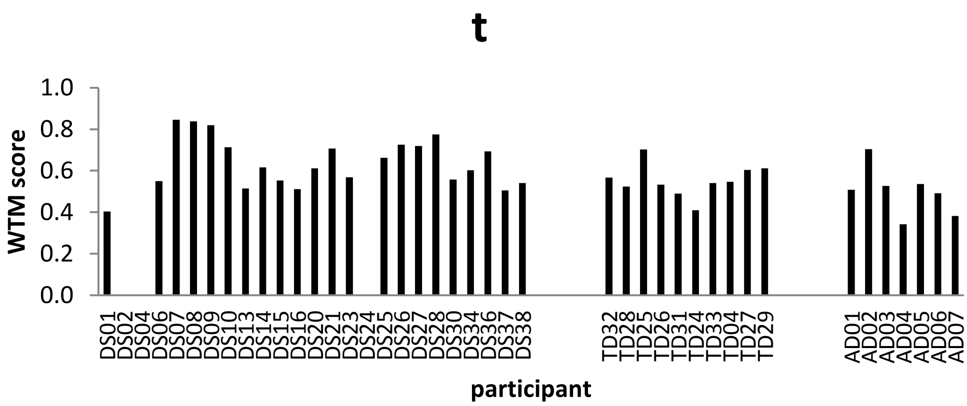


Figure 5-24: Individual WTM scores for perceptually acceptable target /t/ for all speaker groups (DS, TD and AD). TD participants presented in order of age (increasing)

The individual results for perceptually acceptable /s/ (see Figure 5-25) show once more the wide variability in the DS group. A few speakers produce /s/ with more contact than the control groups (DS30, DS28, DS24 and DS02) and many others show very little lingual-palatal contact for perceptually acceptable tokens. The mean between-speaker COV scores for perceptually acceptable target /s/ were DS = 0.43, TD = 0.17, and AD = 0.19 which are the same findings before removal of the perceptual errors.

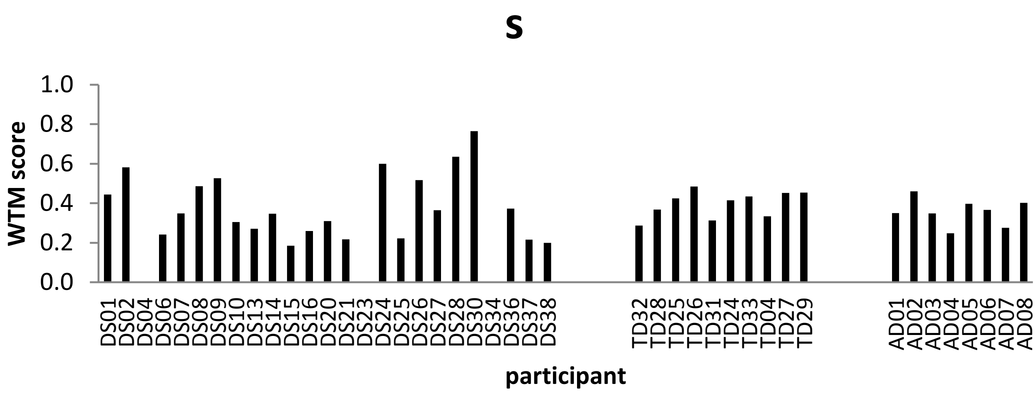


Figure 5-25: Individual mean WTM scores for perceptually acceptable target /s/ for all speaker groups (DS, TD and AD), TD participants presented in order of age (increasing)

The individual WTM scores for perceptually acceptable /ʃ/ are presented in Figure 5-26 below. The scores for the DS group still show a wide range of scores with some speakers producing perceptually acceptable /ʃ/ with very little lingual-palatal contact (DS37 and DS38). The range of scores for the DS group is slightly altered (0.1-0.6), suggesting that productions with high levels of lingual-palatal contact were often errors. The between-speaker COV for DS group is slightly lower than before at 0.34 (compared to 0.47 before removal of perceived inacceptable tokens).

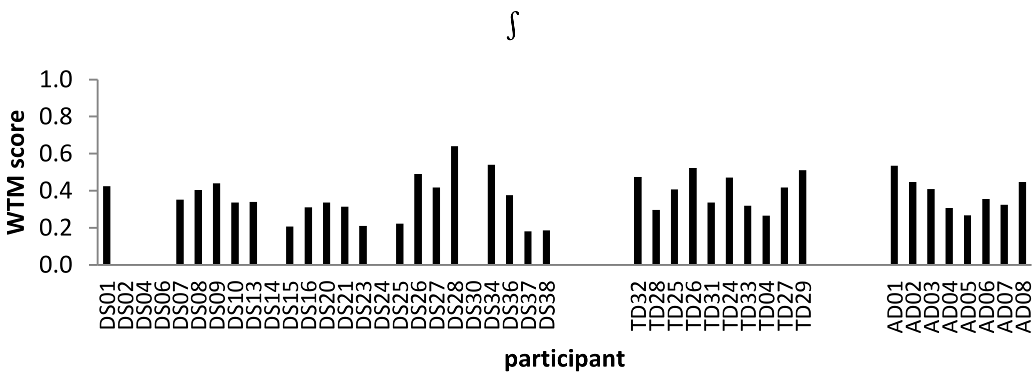


Figure 5-26: Individual WTM scores for perceptually acceptable target /ʃ/ for all speaker groups (DS, TD and AD), TD participants presented in order of age (increasing)

5.3.2.3 Relationship between WTM measures age: TD and DS groups

To investigate the relationship between amount of lingual-palatal contact and age (as this is noted to reduce in typical speakers (Cheng et al. 2007)), correlations were run between the WTM measures and age for both the DS and TD groups (Table 5-9 below). Significant negative relationships were identified for all target sounds for the DS group only.

	WTM /t/	WTM /s/	WTM /ʃ/	WTM_corr /t/	WTM_corr /s/	WTM_corr /ʃ/
DS Age	r=-.402, p=.046	r=-.632, p=.001	r=-.743, p<.001	ns	r=-.500, p=.018	r=-.615, p=.005
TD Age	ns	ns	ns	ns	ns	ns

DS: N=25, TD: N=10;

ns = not significant

Table 5-9: Spearman's Rho correlations for DS and TD chronological age and WTM for target sounds. WTM: whole total contact measure; WTM_corr: WTM scores for perceptually acceptable tokens only

5.3.3 Spatial measurement: Overall spatial variability (OSVar)

Figure 5-27 presents the group scores for overall spatial variability (OSVar) for the target sounds. The DS group present with a higher median score and spread for /t/ OSVar than the TD and the AD group (DS: mean =11.46, SD=5.4; TD mean=6.46, SD=2.5; AD: mean=2.79, SD=1.4). Target /s/ shows a similar pattern for the DS and

TD groups but the DS group presents a much wider spread of scores (DS: mean=9.11, SD=3.5; TD mean=6.97, SD=2.4; AD: mean=3.48, SD=0.8). The DS group shows a slightly higher OSVar mean than the TD group and the AD group still present a low OSVar mean score (DS: mean=9.68, SD=4.8; TD mean= 9.47, SD=1.9; AD: mean=3.53, SD=0.9).

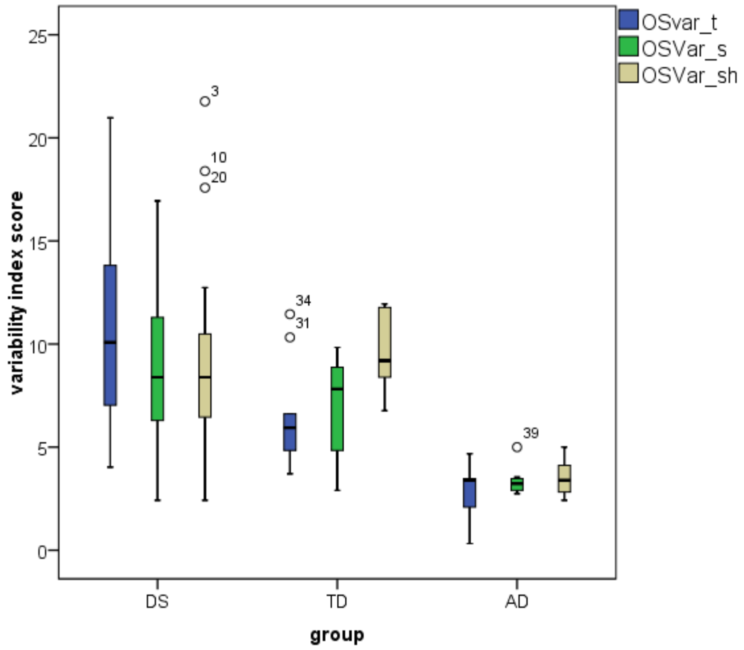


Figure 5-27: Boxplot showing median and IQR values of OSVar (variability index score from all attempted productions of target consonants) for /t/, /s/ and /ʃ/ for DS, TD and AD groups. High scores reflect high levels of spatial variability.

As shown in Table 5-10 there was a significant difference in the OSVar between the DS and TD groups for only /t/, and only significant differences noted between the sibilants in the DS vs AD and TD vs AD comparisons.

	OSVar /t/	OSVar /s/	OSVar /ʃ/
DS vs TD	n = 25 (DS), 10 (TD) U = 44.50 p=.004	ns	ns
DS vs AD	n = 25 (DS), 8 (AD) U = 1.00 p< .001	n = 25 (DS), 8 (AD) U = 8.00 p <.001	n = 25 (DS), 8 (AD) U = 7.00 p <.001
TD vs AD	n = 10 (TD), 8 (AD) U = 2.00 p< .001	n = 10 (TD), 8 (AD) U = 8.00 p= .004	n = 10 (TD), 8 (AD) U = 0.00 p< .001

Bonferroni corrected significance value p=0.0167

ns = not significant

Table 5-10: Results of Mann Whitney U tests for overall spatial variability scores (OSVar) for target sounds in DS, TD and AD groups.

5.3.3.1 Perceptually acceptable spatial variability (PSVar)

The PSVar is a result from the same spatial variability index measure as above but limited to the tokens that were heard as perceptually acceptable. The measure was performed on all three groups for /t/, /s/ and /ʃ/. Figure 5-28 displays the PSVar scores of the annotated /t/, /s/ and /ʃ/ tokens for DS, TD and AD groups.

The data shows a similar pattern to the OSVar measures (though not for target /ʃ/). The DS group present with higher variability scores than the TD and AD groups, for target /t/ and /s/. The mean /t/ PSVar scores for each group were: DS: mean =8.09, SD=3.28; TD: mean=6.46, SD=2.5; AD: mean=2.79, SD=1.4. Target /s/ shows a similar pattern to /t/ with mean PSVar scores: DS: mean=8.41, SD=2.65; TD mean=6.63, SD=2.3; AD: mean=3.48, SD=0.8. Target /ʃ/ shows a different relationship between the DS and TD scores than the previous target sounds, with the TD group presenting with higher variability than the DS group: DS: mean=7.74, SD=3.4; TD: mean= 8.08, SD=3.4; AD = 3.53, SD=0.9.

Mann Whitney U tests (Table 5-11) found no significant differences between the PSVar scores for the DS and TD groups for either of the target sounds. There were significant differences between all three target sounds for the DS vs AD and TD vs AD comparisons.

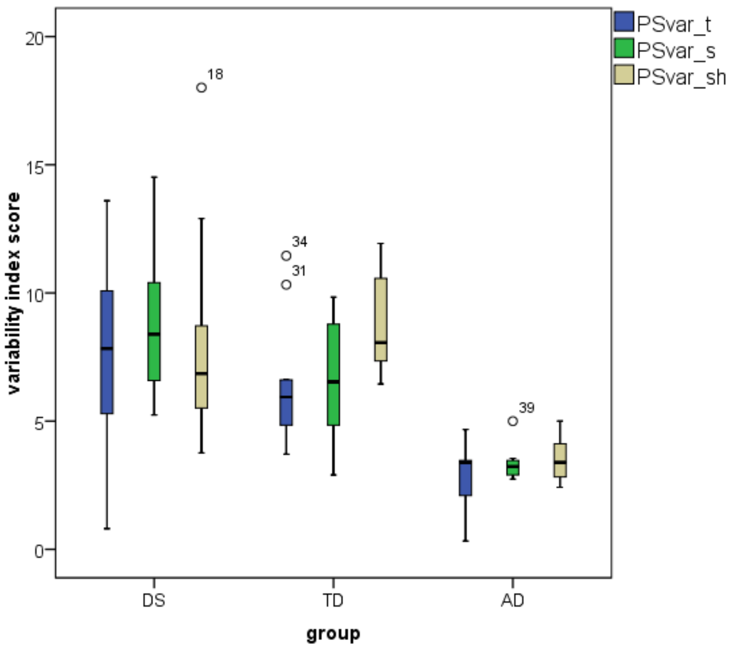


Figure 5-28: Boxplot showing median and IQR values of PSVar (variability index score from only perceptually acceptable productions of target consonants) scores for target consonants /t/, /s/ and /ʃ/: DS, TD and AD groups. High scores reflect high levels of spatial variability.

	PSVar /t/	PSVar /s/	PSVar /ʃ/
DS vs TD	ns	Ns	ns
DS vs AD	n = 25 (DS), 8 (AD) U = 1.00 p< .001	n = 25 (DS), 8 (AD) U = 8.00 p <.001	n = 25 (DS), 8 (AD) U = 4.50 p <.001
TD vs AD	n = 10 (TD), 8 (AD) U = 2.00 p< .001	n = 10 (TD), 8 (AD) U = 8.00 p= .004	n = 10 (TD), 8 (AD) U = 0.00 p< .001

Bonferroni corrected significance value p=0.0167
ns = not significant

Table 5-11: Results of Mann Whitney U tests for perceptually acceptable spatial variability scores (PSVar) for target sounds in DS, TD and AD groups.

5.3.3.2 Relationship between OSVar and PSVar scores for target sounds and age: TD & DS

As spatial variability has been found to decrease as children mature (Cheng et al., 2007ab, Fletcher, 1989), Spearman's Rho correlation was run to check for the effect of age on the OSVar and PSVar scores for both the TD and the DS groups (Table 5-12). No significant correlations were identified for the TD group with age and PSVar/OSVar scores for /t/, /s/ and /ʃ/. Although unexpected this may be related to the small age range and small group size. The DS group presented with no relationship between target sounds and age for most of the spatial measures, though a weak negative connection was identified between age and OSVar /ʃ/. This suggests that older children with DS are more stable in their articulations of /ʃ/ whether produced in error or not.

	PSVar /t/	PSVar /s/	PSVar /ʃ/	OSVar /t/	OSVar /s/	OSVar /ʃ/
DS Age	ns	ns	ns	ns	ns	r=-.432, p=.035
TD Age	ns	ns	ns	ns	ns	ns

DS: N=25, TD: N=10; grey-shading highlights significant relationships

Table 5-12: Spearman's Rho correlations for DS and TD chronological age and spatial variability for target sounds. PSVar: perceptually acceptable spatial variability; OSVar: overall spatial variability

5.3.4 Temporal measure: Duration

The duration measure was only calculated for the perceptually acceptable tokens of the target sounds. This section will present duration measures that were calculated from the perceptually acceptable productions of /t/, /s/ and /ʃ/ for the three speaker groups (DS, TD and AD). The raw duration measures will be presented first and then the COV scores. Interpreting raw measures can be problematic as articulation rate can impact on segment length.

As shown in Figure 5-29, the overall group duration measures show a difference between groups for /t/ production with the DS group showing outliers and a spread towards longer durations compared to shorter periods for the TD and AD group. Although this may not have an influence of the perceptual acceptability of the segment, longer durations may suggest a difficulty with stabilising the complete closure required for acceptable plosive articulation. The fricatives behaved similarly across all three groups and there were no significant relationships for the sibilant durations (as tested by Mann Whitney U tests of comparison).

A look at the individual duration measures for perceptually acceptable productions of /t/ shows a range of durations used in the DS group. Some speakers produce a long closure phase (DS28 and DS36 particularly) and some similar to the AD groups (ranging from 67ms to 160ms). The TD group look similar across the group with durations ranging from 95ms to 225ms.

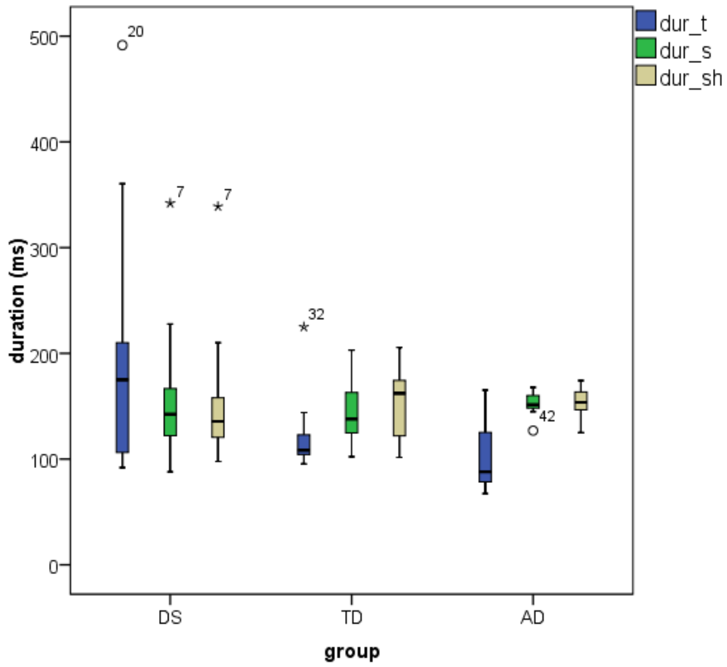


Figure 5-29: Boxplot showing median and IQR values of raw duration measures (ms) for perceptually acceptable /t/, /s/ and /ʃ/ for all speaker groups (DS, TD and AD)

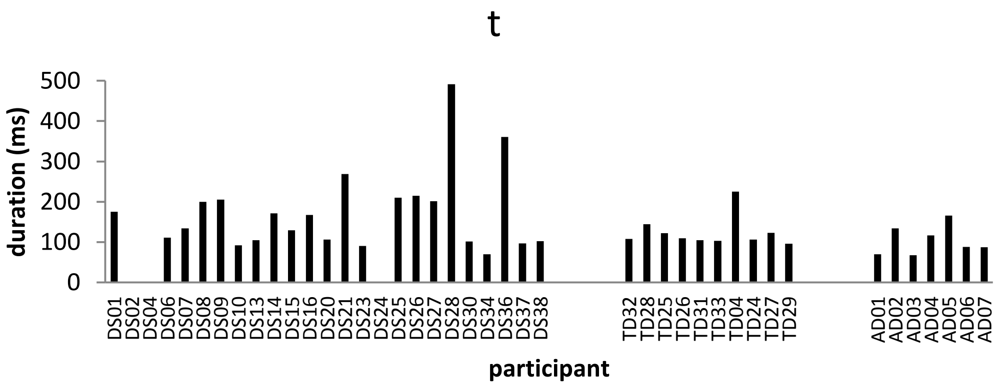


Figure 5-30: Individual duration measures (ms) for /t/ for DS, TD and AD groups. Columns represent mean duration of all perceptually acceptable /s/ segments produced by each speaker, with TD participants presented in order of age (increasing).

Duration measures for target /s/ (Figure 5-31) show that for the AD group there is little between-speaker variation. /s/ ranges between 126ms – 168ms which falls into normal ranges found in previous studies (Greenberg et al., 2003). The TD durations are more variable and range between 104ms-203ms. Clearly the DS are much more variable as a group (range = 87ms-342ms) but show no significant durational differences when compared to the control groups.

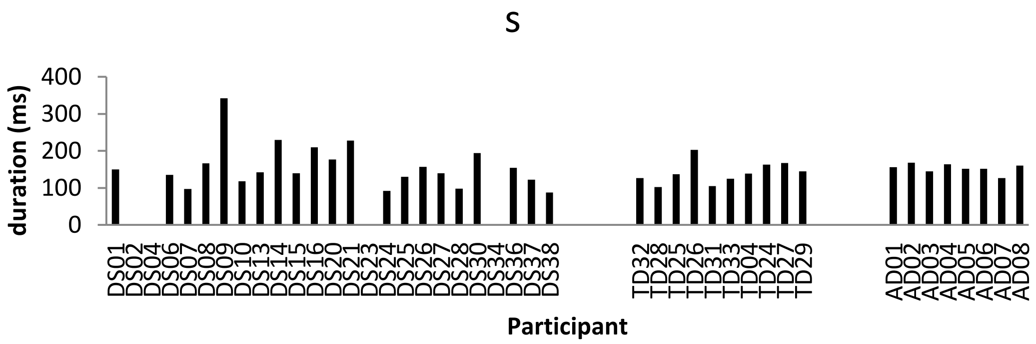


Figure 5-31: Individual duration measures (ms) for /s/ for DS, TD and AD groups. Columns represent mean duration of all perceptually acceptable /s/ segments produced by each speaker, with TD participants presented in order of age (increasing).

A similar pattern appears for /ʃ/ duration (Figure 5-32). The AD control group produce /ʃ/ within 125ms-192ms, slightly longer than the /s/ measures. The TD group are much more variable for /ʃ/ than /s/ (range = 102ms-205ms). This may be explained by the younger ages of some of the TD speakers, reflecting the younger ages of some of the speakers.

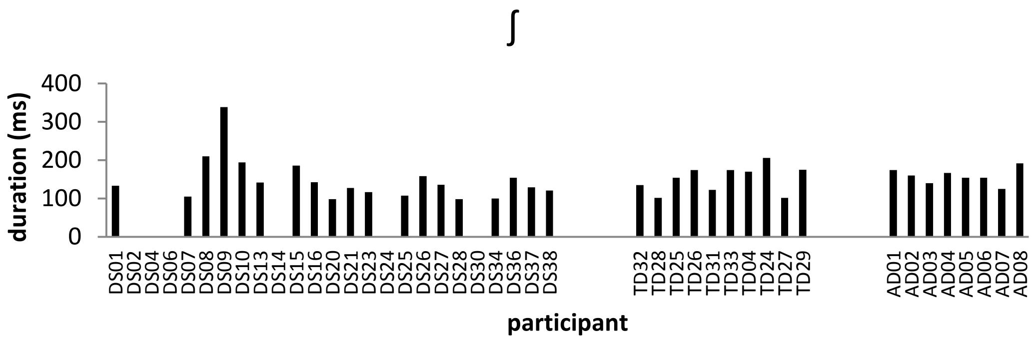


Figure 5-32: Individual duration measures for /ʃ/ for DS, TD and AD groups. Columns represent mean duration of all perceptually acceptable /ʃ/ segments produced by each speaker, with TD participants presented in order of age (increasing).

5.3.5 Temporal measurement: Variability (COV)

As variability is found to increase with longer durations, a COV, as a relative measure, was employed to assess temporal variability (Koenig et al, 2008). The COV measure is presented in Figure 5-33 for the perceptually acceptable tokens of the target sounds. The individual COV scores for the three speaker groups show that the DS group present with higher levels of temporal variability when compared with the

TD and AD groups. Although this is only significant for /s/, between the DS and TD groups (Table 5-13).

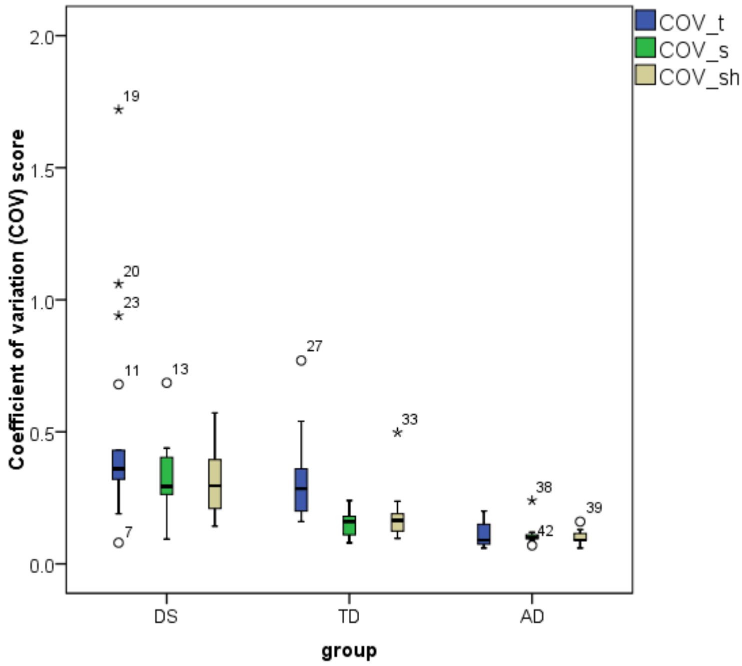


Figure 5-33: Boxplot showing median and IQR values of temporal variability (COV of duration) scores for perceptually acceptable /t/, /s/ and /ʃ/ for DS, TD and AD

	COV /t/	COV /s/	COV /ʃ/
DS vs TD	ns	n = 25 (DS), 10 (TD) U = 15.00 p< .001	ns
DS vs AD	n = 25 (DS), 8 (AD) U = 8.00 p< .001	n = 25 (DS), 8 (AD) U = 10.00 p< .001	n = 25 (DS), 8 (AD) U = 4.00 p< .001
TD vs AD	n = 10 (TD), 8 (AD) U = 3.00 p= .002	Ns	n = 10 (TD), 8 (AD) U = 11.00 p= .010

Bonferroni corrected significance value p=0.0167

ns = not significant

Table 5-13: Results of Mann Whitney U tests for temporal variability scores (COV) for target sounds in DS, TD and AD groups.

5.3.5.1 Correlations of temporal measurements

Spearman’s Rho correlations were performed on the duration measures and the temporal variability measure to assess the impact of longer durations on articulation temporal variability (as noted in typical speech production). No correlations were identified for the TD and AD groups but, as shown in Table 5-14, significant relationships were identified between duration and temporal variability for all target sounds in the DS group data, suggesting that longer segment durations result in higher levels of variability.

	Temporal Variability /t/	Temporal Variability /s/	Temporal Variability /ʃ/
Duration /t/	r=.673, p<.001		
Duration /s/	ns	r=.544, p=.005	
Duration /ʃ/	ns	ns	r=.698, p<.001

N=25; grey-shading highlights significant relationships

Table 5-14: Spearman's Rho correlation scores for duration (ms) vs temporal variability for target sounds (DS group)

5.3.5.2 Relationship between temporal measures and age: TD and DS

As temporal variability is related to maturation of articulation, chronological age was also investigated in relation to these variability measurements. Spearman's Rho correlations identified no relationship for age and the temporal variability measures for the TD group, nor the DS group, which is perhaps unexpected for the TD group, but explained by the low group numbers. Duration measures also presented with no relationship with age for either the DS or TD group.

5.3.6 Relationship between spatial and temporal variability

Studies (Koenig et al, 2008; Smith & Goffman, 1998) note that in typical speech development temporal variability decreases at a slower rate to spatial variability so it may be expected that the TD children would not show a relationship between these measurements in this study. As there is little information on temporal and spatial variability in children with DS, no hypotheses were applied. In order to assess this Spearman's Rho correlations were performed on the OSVar, PSVar, and the temporal variability measures. There were no significant relationships for the DS group but unexpectedly, the TD group presented with a significant relationship for spatial (OSVar and PSVar) and temporal variability measures of /t/ (N=10, r=.716, p=.010), though not the later developing sibilant sounds.

5.3.7 Canonical analysis (CA)

5.3.7.1 Testing the CA training data

Before commencing the testing stage of the CA, the AD data was tested to make sure the training data was accurate and that no errors occurred during the training stage. If the testing worked then we would expect the Mahalanobis distances to be small when testing target /s/ against the training data for /s/, and large when testing against the training data for /ʃ/ and vice versa for testing target /ʃ/. The AD Mahalanobis distances are presented in Figure 5-34 below. As the adult data proved the training data to be useful for CA, the DS and TD data was tested against these data.

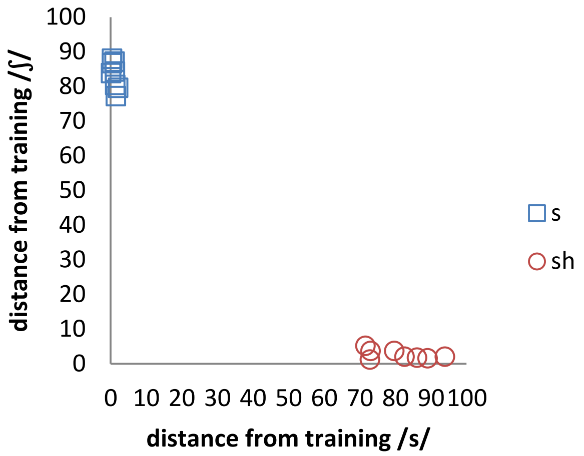


Figure 5-34: Mean AD Mahalanobis distances for /s/ and /ʃ/ from training /s/ and /ʃ/

5.3.7.2 TD Canonical analysis

Figure 5-35 presents the spread for the mean Mahalanobis distances for the TD group. This follows a similar pattern to the AD data. There is a distinction between /s/ and /ʃ/ productions but not as clear as the AD data above. The majority of the target /s/ productions are less than 50 distance points away from target /s/ (except for 2 speakers). However, the target /s/ productions are not as far away from /ʃ/ as expected, with many of the speakers sitting between 20-60 points away (compare this with the AD productions which are all over 70 points away). For the majority of speakers though there is a distinction between the /s/ and /ʃ/ productions.

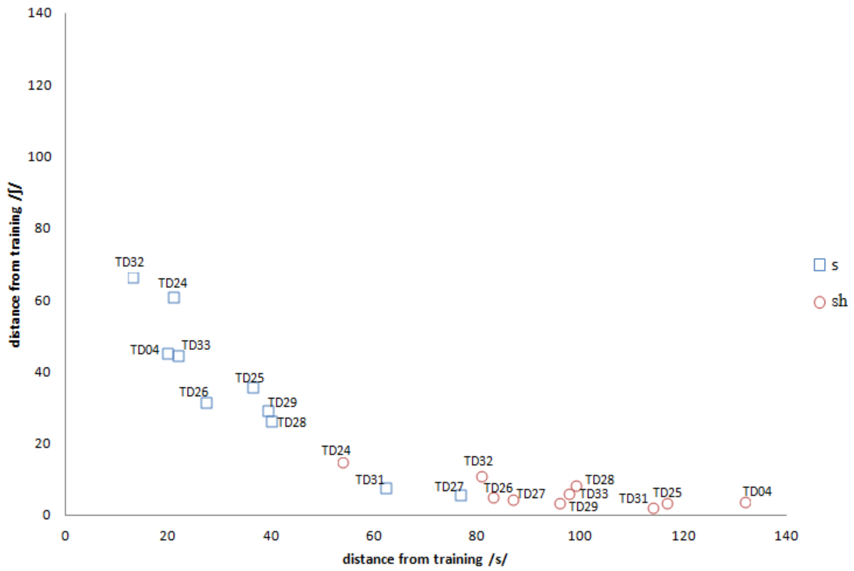


Figure 5-35: Mean TD Mahalanobis distances for /s/ and /ʃ/ from training /s/ and /ʃ/

5.3.7.3 DS Canonical analysis

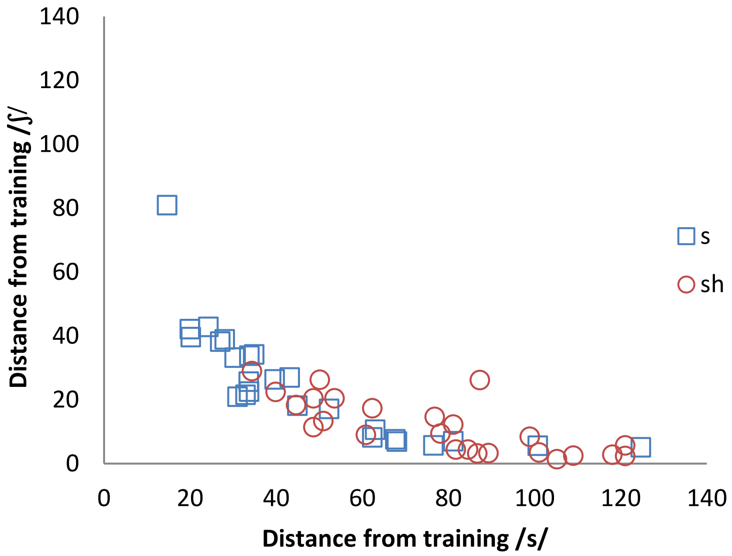


Figure 5-36: Mean DS Mahalanobis distances for /s/ and /ʃ/ from training /s/ and /ʃ/

The DS group Mahalanobis scores (in Figure 5-36) show a greater overlap of the two scores than found for the TD and AD groups. The majority of /s/ productions appear to be closer to /s/ than /ʃ/ although there is a large central overlap of scores. There looks to be more /ʃ/ productions closer to target /ʃ/ pattern than /s/. Individual analysis of these scores will be presented in the case studies chapter.

5.4 Summary of results

This chapter presented the results from the perceptual analysis of the speech data for the three groups of speakers. The main findings of these analyses are presented in 5.4.1 below. The chapter also presented findings from the EPG quantitative analyses, these findings will be summarised in 5.4.2.

5.4.1 Summary of perceptual results

- Children with DS have significantly more difficulties producing adult-like articulation than a cognitively matched group of typically developing children, presenting with significantly lower levels of PTA scores than the TD and AD group for all target sounds.
- No significant relationship for PTA scores and age was identified for the group with DS. However, the TD group presented with a significant relationship for PTA of /ʃ/ and chronological age.
- PE analysis found that productions of target /s/ were most likely to show errors in manner of articulation for the group with DS but there were more errors with place of articulation in the TD group.
- The PE analysis of target /ʃ/ presented a similar pattern of error in both groups with place of articulation more problematic than manner of articulation.
- There were more errors in all 3 features (place, manner and voicing) for both sibilant target sounds for the speakers with DS compared to the TD speakers.
- The group with DS present with higher atypical error patterns than typical (though there is presence of typical substitution) when compared to the TD group.
- The TD group present with a significant negative relationship for the error pattern of *stopping* of target /s/ and chronological age. This does not occur for the group with DS, for any pattern type.

5.4.2 Summary of EPG results

- Speakers with DS show significantly higher levels of spatial variability for overall productions compared to the TD group for /t/ only. Both groups present with significantly higher levels of spatial variability than the AD group.

- The PSVar showed significant differences only between the DS and AD groups (not the DS and TD group). This may be explained by the high levels of /ʃ/ PSVar in the TD group.
- The group with DS show a significant negative relationship for age and OSVar score for /ʃ/ for overall productions. There were no significant relationships between PSVar and age for either the TD group or group with DS.
- COG scores show that most children with DS produce /s/ more anteriorly than /ʃ/ (for both overall productions and perceptually acceptable), though the mean difference between the scores for these two sounds is lower than the mean difference scores for the TD group and the AD group.
- The COV measures of COG scores show that the group with DS are more variable than the TD and AD groups.
- Although not significant, the group with DS show higher levels of lingual-palatal contact for /t/ productions compared to the two control groups
- The COV measures of WTM scores show that the group with DS are more variable than the TD and AD groups.
- There are no duration differences for the three target sounds but temporal COV measures show that the DS group are significantly more variable than the TD group for /s/, and the AD group for all target sounds.
- There were no significant relationships for temporal measures and age for either the TD or group with DS.
- Canonical analysis of the target sibilants noted a wide spread of articulation across the regions of typical /s/ and /ʃ/ production for the group with DS. Speakers showed a lot of articulatory overlap in their productions of these two sounds.

6 Results part two - Descriptive EPG measures

6.1 Introduction

Electropalatography (EPG) analysis allows the visual representation of spatial lingual patterns, and can provide detailed articulatory information that may be missed during perceptual analysis of speech production. These patterns may include atypical articulation patterns unidentifiable to the phonetically trained ear (e.g. undifferentiated gestures (Gibbon, 1999), misdirected articulatory gestures (Hardcastle & Edwards, 1992)).

This chapter will present the results from the descriptive analysis of the articulation patterns used by the participants with Down's syndrome (DS), typically developing children (TD), and typical adult (AD) participants and present the types and ranges of spatial articulation patterns for the target sounds in this study. Results will be presented in box plot figures and tables. Box plots show the median value represented by a black horizontal line, IQR values (25 & 75%) by the height of the box, the range of values between highest and lowest by whiskers above and below the box. Outliers are represented by circles and stars.

The results are presented in order of methodology rather than research questions. The results presented in this following chapter will help to answer RQ1 and RQ3:

RQ1 – Do children with DS show more atypical articulation patterns in errors of sibilant production in comparison to TD and typical AD?
RQ3 - Do children with DS present with atypical EPG measures and patterns for perceptually acceptable productions of sibilants?

The results below are also provided to help support **H6** and **H13**:

- Overall group results (DS, TD and AD) for typical pattern use in the three target sounds
- % of pattern types used by the DS group for /t/ in comparison to the TD and AD groups

- % of pattern types used by the DS group for /s/ in comparison to the TD and AD groups
- % of pattern types used by the DS group for /ʃ/ in comparison to the TD and AD groups
- Correlations of pattern types, with perceptual analysis findings and chronological age.

The results will show that our understanding of articulation ability in children with DS and our knowledge of lingual-palatal articulations in typically developing children (particularly those who are still in the process of speech acquisition) is not yet complete. The typical dataset used in this study is small (as illustrated in Table 6-1), and this will be taken into account in the discussion chapter.

		/t/		/s/		/ʃ/	
	No. of speakers	Total no. of repetitions	% productions perceptually acceptable	Total no. of repetitions	% productions perceptually acceptable	Total no. of repetitions	% productions perceptually acceptable
DS	25	240	*71*	246	*61*	231	*44*
TD	10	98	*100*	100	*94*	99	*86*
AD	8	80	*100*	79	*100*	80	*100*

Table 6-1: Number of speakers and total number of repetitions for each participant group (DS: Down's syndrome; TD: Typically Developing; AD: Adult) and target sound (/t/, /s/ and /ʃ/).

6.2 EPG Pattern Analysis

6.2.1 Analysis

Each target sound was analysed with reference to a typical (standard pattern) in order to calculate a percent pattern acceptable score. The other patterns are then referred to as other (non-typical) patterns. This nomenclature is perhaps misleading as it does not refer to pattern types that are atypical in speech development, rather, the other patterns are not the typical standard EPG pattern (as defined in the literature).

This analysis was based on the most prominent pattern across the duration of the EPG annotation (to be precise, this was the pattern shown across the majority of EPG frames). This provides a slightly enhanced look at the speaker's articulatory behaviour for the target sounds (compared to a single frame of maximum contact). A single frame, as presented in Chapter 5, may not be sufficient for the investigation of speakers with inconsistent articulation patterns. This can be particularly limiting for an analysis of articulatory stability, as it ignores the kinematics involved throughout the articulation. Furthermore a frame of maximum constriction can often be misleading and may mask the presence of the more atypical productions such as articulatory drift, or even typical productions, e.g. affricates. Recent investigations (Iskarous, Shadle & Proctor, 2011; Reidy, 2015) of spectral measures of sibilant productions have noted that static measures are insufficient to characterise acoustic patterns. For example, Iskarous et al. (2011) identified changes in tongue and jaw position during the sibilant. Similar investigations using EPG are yet to materialise, though dynamic patterns are often presented in small scale studies where dynamics can be presented and described. The descriptive patterns presented here were an attempt to classify and represent the whole articulation for a large group of speakers.

The typical patterns identified in the descriptive analysis were established via consultation from the literature and the available AD data in this study. The following definitions were then provided (see Figure 6-1 for example patterns):

- Typical alveolar stop pattern: Alveolar Closure (Row 1, may extend to row 4) with lateral bracing
- Typical alveolar fricative pattern: Narrowest groove (1-3 electrodes) at alveolar region (rows 1-2) with lateral bracing. May be asymmetrical
- Typical post alveolar fricative pattern: Narrowest groove (1-3 electrodes) at post-alveolar region (rows 3-4) with lateral bracing. May be asymmetrical

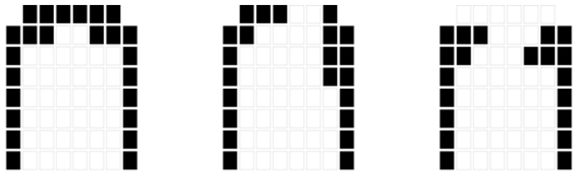


Figure 6-1: Typical static EPG patterns for target /t/, /s/ and /ʃ/, taken from AD productions

6.2.2 Overall group results for /t/, /s/ and /ʃ/ typical pattern use

The following chart (Figure 6-2) presents median and interquartile range (IQR) values of the percentage of typical pattern (see 3.8 for detail on score calculation) use for each target sound for each speaker group.

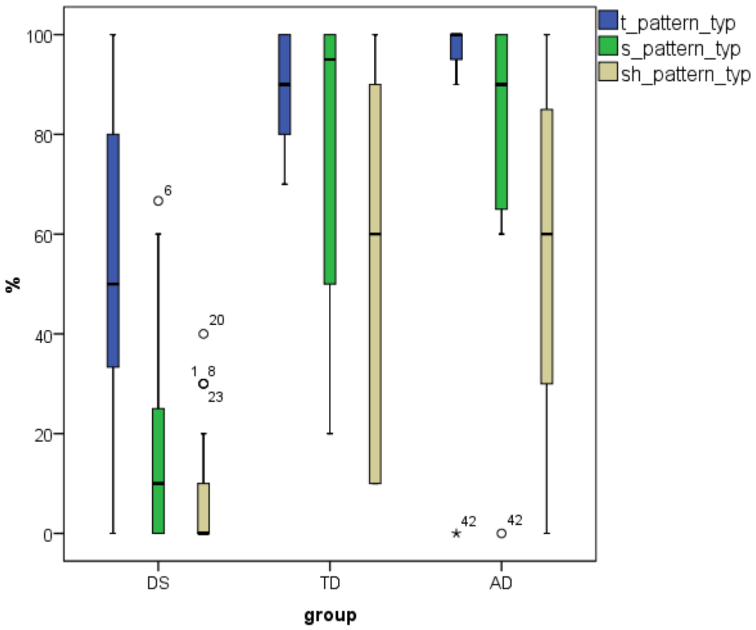


Figure 6-2: Boxplot showing median and IQR values of percentages of typical articulation pattern types (pattern_typ) identified in productions of target /t/, /s/ and /ʃ/ for DS, TD and AD groups

The TD and AD group present with similar results for the use of the typical patterns for the three target sounds. All groups show less typical pattern use for /ʃ/ than the other target sounds (the possible reasoning for this will be discussed in 8.2.3). The TD group present with significantly higher use of the typical pattern types than the DS group for all three target sounds (see Table 6-2). The DS group used the typical pattern for 53% of productions of /t/, compared to 92% for the TD group. For target /s/ production, the DS group only produced 16% compared to 84%

for the TD group. And finally for target /ʃ/, the DS group score was 8% compared to 61% for the TD group.

	Typical patterns /t/	Typical patterns /s/	Typical patterns /ʃ/
DS vs TD	n = 25 (DS), 10 (TD) U = 33.50 p=.001	n = 25 (DS), 10 (TD) U = 15.50 p<.001	n = 25 (DS), 10 (TD) U = 29.00 p<.001
DS vs AD	n = 25 (DS), 8 (AD) U = 29.50 p=.006	n = 25 (DS), 8 (AD) U = 20.50 p<.001	n = 25 (DS), 8 (AD) U = 22.00 p =.001
TD vs AD	Ns	ns	Ns

Bonferroni corrected significance value p=0.0167

ns = not significant

Table 6-2: Results of Mann Whitney U tests for typical pattern % scores for target sounds in DS, TD and AD groups.

6.2.3 /t/ pattern results

As noted in Figure 6-2, the number of typical patterns used by the AD and TD groups for target /t/ is significantly larger than the DS group. Table 6-3 below presents the percentage of each pattern type identified in production of /t/ for the DS, TD and AD groups. Scores are provided for the percentage of each pattern type used for all productions of the target sound, the perceptually acceptable tokens and the errors. Numbers of speakers using each pattern are provided in brackets.

Most of the AD speakers used the typical alveolar stop pattern for production of /t/. 84% of productions were classified as typical, with other pattern types accounting for 16% of productions. 10 of these productions were all from AD6 who produced /t/ with *anterior closure with lack of lateral seal.* This pattern was also noted in 1 production by AD4.

The TD group produce no errors for /t/ production and the patterns produced include: *typical pattern, incomplete closure, anterior closure with lack of lateral seal, retracted anterior closure* and *double articulation.* The numbers are small but there is evidence of patterns unidentified in EPG analysis of typical speech production to date (see 8.5.1 for more discussion). *Incomplete closure* is the second most common pattern used by the TD speakers for /t/ production. This is unexpected but has been noted in other EPG studies for older children (e.g. Cheng et al. 2007, though see 8.5.1 for more discussion). This was used by 2 speakers (TD24 and TD29, two of the older participants). The *retracted anterior closure* pattern was used by one speaker (TD32), and, although not classed as the typical pattern, the speaker produces a similar horseshoe articulation shape which may result in a release that sounds acceptable (due to the contact shape being the same, albeit retracted). *Double articulation* is used once by TD32 and was identified for a perceptually acceptable production. The presence of alveolar-velar double articulations in typical speech has to the author's knowledge, never been reported (see 8.2.3 for implications of this). *Anterior closure with lack of lateral seal* is used once by 2 speakers (TD28 and TD31). While these patterns are used minimally this raises questions about what could be considered typical when analysing the experimental group.

The pattern analysis was based on the overall pattern observed during the closure phase of /t/ production. However, our perception of a plosive is based on the release phase, not the closure phase. The pattern analysis for /t/ was also completed for the EPG frame immediately prior plosive release. This analysis found that there were no differences in the patterns identified immediately prior to release to those identified in the pattern analysis.

The DS group show *typical pattern* as the most common pattern for overall productions, perceptually acceptable tokens and the tokens produced in error. More atypical patterns were identified for target /t/ in the DS group compared to the TD group overall. The most common of these patterns were *undifferentiated gesture, double articulation* and *retracted anterior closure.* Both *undifferentiated gesture* and *double articulation* were identified in the articulations of 10 of the DS speakers, and *retracted anterior closure* was noted in 9 speakers. *Minimal contact, full anterior closure* and *incomplete closure* were also identified. Of these, *incomplete closure* was used by 10 of the DS speakers, *full anterior closure* by 6 and *minimal contact* by 4. A very small number of productions were identified as being produced with *posterior articulation* and *lack of lateral seal.* All the DS speakers present with at least one atypical pattern, or patterns.

Comparing the DS and TD data (Table 6-3 below), reveals that the DS group are using a wider range of patterns not identified in /t/ articulation in TD children. Patterns that appear only in the DS group productions of target /t/ are: *posterior articulation, full anterior closure, undifferentiated gesture, minimal contact,* and *lack of lateral seal.*

Pattern Type	DS (N=25) % overall n = 240	% perceptually acceptable n=170	% errors n=70	TD (N=10) % overall n=98	% perceptually acceptable	% errors	AD (N=8) % overall n=80	% perceptually acceptable	% errors
/t/									
typical pattern	**55.4 (23)**	**67.6 (20)**	**27.3 (23)**	**91.8 (10)**			**84.3 (8)**		
undifferentiated gesture	10.0 (10)	5.3 (5)	18.2 (10)						
double articulation	8.8 (10)	10.6 (10)	5.2 (10)	1 (1)					
retracted anterior closure	7.5 (9)	7.1 (8)	9.1 (9)	2 (1)					
minimal contact	5.0 (3)		15.6 (4)						
incomplete closure	6.3 (10)	5.9 (6)	10.4 (10)	3.1 (2)					
full anterior closure	6.3 (6)	3.5 (4)	3.6 (6)						
posterior articulation	0.4(1)		1.3 (1)						
anterior closure w/ lack of lateral seal				2 (2)			15.7 (2)		
lack of lateral seal	0.4 (1)		1.3 (2)						

Table 6-3: Percentage scores of pattern types for target /t/ for DS, TD and AD groups. Table presents percentages for overall productions, perceptually acceptable productions and errors. Numbers of speakers showing evidence of pattern types in brackets. Bold numbers show highest scores in each column.

The main pattern identified for perceptually acceptable productions of /t/ in the DS group is the typical alveolar plosive pattern (67%, number of speakers=20). Most of the *other* pattern types identified for all attempts at target /t/ are evident in the perceptually acceptable data. The following patterns are not evident in the DS data for perceptually acceptable productions: *minimal contact, lack of lateral seal* and *posterior articulation.* However, some of the more atypical articulations (e.g. *undifferentiated gesture)* were identified as articulations used for perceptually acceptable productions. These included: *double articulation* (10 speakers), *retracted anterior closure* (8 speakers), *incomplete closure* (6 speakers) *undifferentiated gesture* (5 speakers) and *full anterior closure* (4 speakers). Other patterns were used by 5 speakers or less. Some of these patterns were also identified in the TD speakers (except *undifferentiated gesture* and *full anterior closure*) for perceptually acceptable productions.

The DS group also presented with a wide range of patterns for /t/ errors, these included high numbers of *typical pattern, undifferentiated gesture* and *minimal contact.*

6.2.4 /s/ pattern analysis

Table 6-4 below presents the percentage of each pattern type identified in production of /s/ for the DS, TD and AD groups. Scores are provided for the percentage of different pattern types used for all productions of the target sound, the perceptually acceptable tokens and the errors.

The AD group produced no perceptual errors for productions of /s/, but the results from the pattern analysis did not identify 100% use of the typical pattern. The analysis of /s/ productions by the AD group showed 77.5% patterns classified as typical articulations. Of the 22.5% non-typical patterns, 1 of these was a production with a *wide groove* pattern (this is the only occurrence of this in the AD data for /s/). The other non-typical productions were all *lack of lateral seal*. This pattern was used by 3 speakers, and two of the AD speakers used this pattern for all ten productions of /s/.

As shown in Table 6-4, the number of typical patterns identified for target /s/ in the TD repetition data is larger (79%) than the other patterns (21%). Not all tokens of target /s/ were perceptually acceptable (94%), suggesting other articulation patterns as well as the typical alveolar fricative pattern were used. The other patterns identified for target /s/ production in the TD speakers were: *wide groove, retracted pattern, complete alveolar closure, lack of groove* and *affricate* (these patterns were also identified in the perceptually acceptable tokens). *Wide groove* is the most common of the other patterns for /s/ productions, used by 4 speakers, with only one token produced as an error (TD04 = [ʃ]). The *retracted articulation* pattern was observed 6 times in only one speaker (TD31, who produced all target /s/ as perceptually acceptable). *Complete closure* was noted twice in TD04 (both these productions were heard as [t]). *Lack of groove* was also observed as a pattern for target /s/ in one production by TD04 (heard as [t̪]) and once for TD31 (heard as acceptable). The final pattern *affricate* was used twice by TD28 (one of the youngest speakers) and was heard both times as being a perceptually acceptable /s/.

The DS group presented with a wider range of articulation patterns for target /s/ than the TD group. The most common patterns overall were *typical pattern* (14 speakers), *complete alveolar closure* (10 speakers), *lack of groove* (11 speakers), *wide groove* (8 speakers), *minimal contact, anterior closure with lack of lateral seal* and *retracted pattern.* There is also evidence (in less than 5 speakers) of *lack of lateral seal, double articulation, lateral fricative, anterior groove and velar constriction, affricate, velar constriction with lateral contact, undifferentiated gesture* and *articulatory drift.*

The most common patterns for the DS group were also identified in the TD group but very minimally (*complete alveolar closure* and *lack of groove*). The presence of these in both groups indicates that the DS group are producing patterns expected in typically developing children, but also many patterns not found in typically developing children. These patterns are: *undifferentiated gesture, double articulation, lateral fricative, anterior groove and velar constriction, minimal contact, lack of lateral seal, anterior closure with lack of lateral seal, velar constriction with lateral contact* and *articulatory drift.*

Pattern Type	DS (N=25) % overall n=246	DS (N=25) % perceptually acceptable n=152	DS (N=25) % errors n=94	TD (N=10) % overall n=100	TD (N=10) % perceptually acceptable n=94	TD (N=10) % errors n=6	AD (N=8) % overall n=79	AD (N=8) % perceptually acceptable	AD (N=8) % errors
/s/									
complete alveolar closure	**22.8 (10)**	14.5 (8)	**38.7 (8)**	3 (2)	1.1 (1)	**33.3 (1)**			
alveolar fricative pattern	16.2 (14)	17.1 (12)	12.9 (7)	**79 (10)**	**81.9 (10)**	**33.3 (2)**	**77.5 (7)**		
lack of groove	15.1 (11)	**17.8 (10)**	10.8 (5)	2 (2)	2.0 (1)	16.7 (1)			
wide groove	10.9 (8)	15.1 (7)	2.2 (2)	8 (4)	7.4 (3)	16.7 (1)	1.3 (1)		
anterior closure with lack of lateral seal	8.1 (3)	10.5 (3)	4.3 (1)						
minimal contact	6.1 (6)	4.6 (3)	8.6 (3)						
retracted pattern	4.9 (6)	7.2 (6)	3.2 (2)	6 (1)	6.4 (1)				
lack of lateral seal	4.1 (2)	6.6 (2)					21.5 (3)		
velar constriction with lateral contact	2.4 (2)	1.3 (1)	3.2 (1)						
double articulation	2.0 (4)	3.3 (5)	1.1 (1)						
anterior groove + velar constriction	2.0 (2)	1.9 (1)	2.2 (2)						
lateral fricative	2.0 (1)		5.4 (1)						
affricate	1.6 (3)		4.3 (3)	2 (1)	2.1 (1)				
undifferentiated gesture	1.2 (2)		2.2 (2)						
articulatory drift	0.4 (1)		1.1 (1)						

Table 6-4: Percentage scores of pattern types for target /s/ for DS, TD and AD groups. Table presents percentages for overall productions, perceptually acceptable productions and errors. Numbers in brackets represent number of speakers showing evidence of pattern types. Bold numbers show highest scores in each column.

Pattern scores for the DS perceptually acceptable tokens of /s/ show 17% alveolar fricative patterns identified and 84% other patterns. As illustrated in Table 6-4 there are a few patterns only evident in tokens produced in error (*undifferentiated gesture, lateral fricative, affricate* or *articulatory drift).* All other patterns were present during tokens considered perceptually acceptable. Similarly the TD group show evidence of patterns other than the *alveolar fricative pattern* for perceptually acceptable tokens (*wide groove, retracted pattern, complete alveolar closure, lack of groove* and *affricate),* though in small numbers. There were also many articulation patterns present in the DS data that weren't identified in the TD data for productions of perceptually acceptable tokens. These patterns were: *double articulation, anterior groove and velar constriction, minimal contact, lack of lateral seal, anterior closure with lack of lateral seal* and *velar constriction with lateral contact.* The most common patterns identified for the DS errors were *complete alveolar closure, typical pattern* and *minimal contact.*

6.2.5 /ʃ/ pattern results

Table 6-5 below presents the percentage of each pattern type identified in production of /ʃ/ for the DS, TD and AD groups. Scores are provided for the percentage of different pattern types used for all productions of the target sound, the perceptually acceptable tokens and the errors.

The AD group produce no errors for target /ʃ/ production and present with 61% of tokens identified as typical articulation patterns. The most common of the other patterns was *wide groove* (20%) which was used by 5 of the 8 speakers for /ʃ/ production. *lack of groove* (14%) was used by 2 speakers, with one speaker using it for 90% of their productions. The other patterns were used minimally: *fronted groove* (3 occurrences), *velar constriction with lack of lateral seal* (once).

In the TD group, 61% of the patterns identified in all attempted productions of target /ʃ/ were typical post-alveolar pattern types. The majority of *other* patterns were identified as *fronted groove* patterns (13% of productions). Four speakers used this pattern (TD25, TD27, TD28 and TD32) with TD28 using it 6/10 times, TD32 using it 5/10 times and TD25 and TD27 using it only once each. *Velar constriction with lateral contact* is the next most popular pattern (8% of productions), used by 3 of the speakers (TD25, TD26, TD32). All of these productions were heard as perceptually acceptable. *Lack of groove* is used for 6% of productions, by 4 speakers (TD04, TD25, TD27, and TD28). For 2 of these speakers (TD25, TD27) this pattern only occurs once (it appears twice for the other two speakers, TD04 and TD28). Aside from one of the productions of /ʃ/ by TD28 (heard as [s]), all of those patterns classed as *lack of groove* were considered to be perceptually acceptable. *Anterior groove and velar constriction* was used for 6% of the productions. Two speakers used this pattern, TD32 only once but TD26 used this as their preferred pattern of articulation for this target sound (these were all heard as perceptually acceptable productions of /ʃ/). *Wide groove* pattern was identified for 5% of the productions, used once by 3 speakers (TD04, TD26, TD31) and twice for TD33. *Wide groove* was mostly used in perceptually acceptable tokens (except once for TD33). These results suggest that for target /ʃ/ groove width can be variable or not evident and the production would still be perceived as an acceptable [ʃ] production. These numbers are low but provide important information about the range of articulation patterns used by typical speakers, showing the articulatory changes that are normal in phonological development.

The pattern and perceptual relationship does not follow any clear pattern. There are a wide variety of patterns used which are clearly dissimilar to the standard typical production (e.g. *velar constriction with lateral contact* and *anterior groove with velar constriction*). The other non-typical patterns (*lack of groove* and *wide groove)* have been identified within the normal ranges of articulation for /ʃ/ in previous literature. When productions were not heard as perceptually acceptable, again there is no clear relationship between pattern and perception. TD25 uses a *fronted groov*e pattern for a production of target /ʃ/ which was perceived as an alveolar fricative [s]. TD28 has an affricate pattern identified for target /ʃ/ which was perceived as a post-alveolar affricate. TD32 displays a few *fronted groove* patterns, but these are all perceived as [ʃ] (further discussion of this will be presented in 8.2.3).

Pattern Type	DS (N=25) % overall n=231	DS (N=25) % perceptually acceptable n=108	DS (N=25) % errors n=123	TD (N=10) % overall n=99	TD (N=10) % perceptually acceptable n=87	TD (N=10) % errors n=12	AD (N=8) % overall n=80	AD (N=8) % perceptually acceptable	AD (N=8) % errors
/ʃ/									
lack of groove	**23.4 (14)**	**32.4 (10)**	**17.2 (10)**	6.1 (4)	5.74 (4)	5.3 (1)	13.8 (2)		
fronted groove	14.3 (12)	12.0 (8)	16.4 (10)	13.1 (4)	5.74 (2)	**42.1 (3)**	3.8 (2)		
typical pattern	8.7 (10)	12.0 (8)	7.0 (6)	**60.6 (10)**	**68.9 (9)**	5.3 (1)	**61.3 (7)**		
complete alveolar closure	8.7 (7)	0.9 (1)	13.3 (6)						
wide groove	8.2 (5)	14.8 (5)	2.3 (2)	5.1 (4)	4.6 (4)	5.3 (1)	20 (4)		
velar constriction with lateral contact	6.1 (4)	5.5 (3)	6.2 (2)	8.1 (3)	6.9 (2)	5.3 (1)	1.3 (1)		
lack of lateral seal	5.6 (2)	6.5 (2)	5.5 (2)						
double articulation	3.9 (7)	4.6 (3)	3.1 (4)						
anterior groove + velar constriction	3.9 (3)	6.5 (3)	1.5 (1)	6.1 (2)	6.9 (2)	31.8 (2)			
articulatory drift	3.3 (4)	1.8 (1)	3.9 (4)						
minimum lateral contact	3.4 (6)		7.0 (6)						
undifferentiated gesture	3.9 (1)		7.0 (1)						
affricate	3.5 (6)	2.7 (2)	3.8 (4)	1.0 (1)	1.1 (1)	5.3 (1)			
anterior closure with lack of lateral seal	3.0 (1)		5.5 (1)						

Table 6-5: Percentage scores of pattern types for target /ʃ/ for DS, TD and AD groups. Table presents percentages for overall productions, perceptually acceptable productions and errors. Numbers in brackets represent number of speakers showing evidence of pattern types. Bold numbers show highest scores in each column.

The DS group present with 8.7% of typical patterns for productions of /ʃ/. The most common pattern type identified for target /ʃ/ was *lack of groove* (23.4%), occurring in the productions of 14 of the speakers, followed by *fronted groove* (14%) used by 10 speakers and *typical pattern* and *complete closure* (8.7%). Other patterns were: *wide groove, velar constriction with lateral contact,* and *lack of lateral seal.* A small number of productions were identified as being *double articulation, anterior groove and velar constriction, articulatory drift, affricate, minimum lateral contact,* and *anterior closure with lack of lateral seal.*

The DS and TD group display some similar patterns for target /ʃ/ productions. Both *lack of groove* and *fronted groove* are noted in the two groups (in the DS group these are the most popular patterns) suggesting that the DS group are sometimes producing similar articulation patterns to the TD group. There are similar mean scores for the use of *fronted groove* as a pattern type for target /ʃ/. This is the only pattern type that displays a similar score, though, as noted, it is not the only pattern type shared by the two groups. The TD group show a higher score for *velar constriction with lateral* than the DS group. This is also seen in the scores for *anterior groove and velar constriction.* The patterns not evident in the TD group are *complete alveolar closure, double articulation, articulatory drift, minimum lateral contact, anterior closure with lack of lateral seal, lack of lateral seal* and *undifferentiated gesture.*

While the expected alveolar fricative pattern is used by most speakers in all three groups, there is evidence of other patterns used for perceptually acceptable productions. There are many participants (10 speakers) in the DS group using the *lack of groove* pattern for perceptually acceptable /s/ production. *Wide groove* shows a score of 14% but only in 5 speakers. The other common patterns were *fronted groove* and *typical pattern* (both 11.5% from 8 speakers). The only patterns identified only for errors in the DS group were: *undifferentiated gesture* and *anterior closure with lack of lateral seal.*

6.2.6 Relationship between pattern analysis results and age

Spearman's Rho correlations were performed to assess the relationship between various pattern measures and age for both the TD and DS groups. It was expected that the TD children would show patterns of articulation maturation across the ages and would show increased use of the typical patterns with age. In order to investigate this, the percentage typical pattern scores were correlated with chronological age.

	Typical patterns /t/	Typical patterns /s/	Typical patterns /ʃ/
DS Age	ns	r=-.530, p=.006	ns
TD Age	ns	ns	r=.734, p=.016

N=10; grey-shading highlights significant relationships

ns = not significant

Table 6-6: Spearman's Rho correlation scores for age vs typical patterns for target sounds (DS and TD group)

There was no relationship with age and use of typical pattern for /t/ and /s/ in TD production, though this may be related to the limitations on the pattern types considered to be typical and the small TD group size. A weak significant relationship was identified for age and increased use of the typical pattern for /ʃ/ in the TD group. A different pattern appears for the DS group who show a negative relationship with chronological age and the use of the typical alveolar grooved pattern for target /s/. This may be related to the narrow definition provided in this study for typical articulation of /s/, or may reflect the atypical speech patterns in this group of speakers with DS.

The use of the patterns reflecting fronting of target /ʃ/ (*fronted groove)* and stopping of target /s/ (*complete alveolar closure)* were also correlated against age. As a typical process, it may be expected that the *fronted groove pattern* and *complete closure* would be noted in the younger speakers rather than the older. Spearman's Rho correlations found no significant relationships between the use of these pattern types and age for either the DS or TD groups.

6.2.7 Relationship between perceptual analysis and pattern analysis

In order to investigate the relationship between perceptual analysis (as measured by the PTA score) and the pattern analysis, Spearman's Rho correlations were run between the PTA measures for all target sounds and the percentage of typical patterns identified. Results are presented in Table 6-7. The only significant relationships emerge between typical patterns for /t/ and the PTA scores for /t/ in the DS group, and for /ʃ/ in the TD group.

	PTA /t/	PTA /s/	PTA /ʃ/
DS			
%typical patterns /t/	r=.758, p<.001		
%typical patterns /s/		ns	
%typical patterns /ʃ/			ns
TD			
%typical patterns /t/	ns		
%typical patterns /s/		ns	
%typical patterns /ʃ/			r=.792, p=.006

DS: N=25, TD: N=10; grey-shading highlights significant relationships
ns = not significant

Table 6-7: Spearman's Rho correlation scores for % typical patterns vs PTA for target sounds (DS and TD group). PTA: Perceptually acceptable target score

In the error pattern analysis, typical errors were identified as *stopping* (of target /s/) and *fronting* (of target /ʃ/). Spearman's Rho correlations were run to investigate whether there was a relationship between EPG patterns identified as *complete alveolar closure* (for target /s/ productions) and perceptual errors classed as *stopping*, and similarly for EPG patterns identified as *fronting* (for target /ʃ/ productions) and perceptual errors classed as *fronting.*

	perceptual error: stopping /s/	perceptual error: fronting /ʃ/
TD complete alveolar closure pattern	r=1.000, p<.001	
TD fronted groove pattern		r=.885, p=.001
DS complete alveolar closure pattern	ns	
DS fronted groove pattern		r=.434, p=.030

TD N=10, DS N=25 grey-shading highlights significant relationships
ns = no significance

Table 6-8: Spearman's Rho correlation scores for perceptual error types: fronting and stopping vs pattern error types: complete alveolar closure and fronted groove (DS and TD group)

The TD group show a clear relationship between the pattern analyses reflecting stopping and fronting, and the perceptual error patterns reflecting the same. The DS group present with a different pattern, with no evidence of a relationship between perceptual and pattern categorisation for 'stopping' but this may be expected considering the range of perceptual errors that were identified in this group compared to the TD speakers. However, the DS group also present a weak correlation between the perception of fronting and the visual categorisation of the EPG patterns as fronting.

6.3 Summary of results

This chapter presented the results from the descriptive pattern analysis. This analysis was a categorisation exercise based on visual analysis of the annotated regions for the target sounds /t/, /s/ and /ʃ/. This was applied to all data from the TD and DS groups and then further applied to only the perceptually acceptable tokens.

The analysis of target /s/ found that:

- The TD and DS group showed 6 similar pattern types for /s/ production.
    - The most common pattern for the TD group was *typical alveolar fricative.*
    - The most common pattern for the DS group was *complete alveolar closure.*
    - The DS group used 9 different pattern types for all target /s/ productions.
- The TD and DS group also showed 6 similar pattern types for perceptual acceptable tokens of /s/.
    - The most common pattern for the TD group was *typical alveolar fricative*
    - The most common pattern for the DS group was *lack of groove*
    - The DS group used 6 different pattern types for perceptually acceptable /s/ production.

The analysis of target /ʃ/ found that:

- The TD and DS group showed 7 similar pattern types for /ʃ/ production.
    - The most common pattern for the TD group was *typical post-alveolar fricative*
    - The most common pattern for the DS group was *lack of groove.*
    - The DS group used 7 different pattern types for all target /s/ productions.
- The TD and DS group also showed 7 similar pattern types for perceptual acceptable tokens of /ʃ/.
    - The most common pattern for the TD group was *typical post-alveolar fricative*

- The most common pattern for the DS group was *lack of groove*
- The DS group used 4 different pattern types for perceptually acceptable /ʃ/ production.

The TD group used significantly more typical patterns for the target fricatives than the DS group. Atypical articulation patterns were detected in the DS group for all productions of all three target sounds. This finding was replicated in the analysis of the perceptually acceptable tokens.

This chapter provided detail regarding the wide range of patterns used for perceptually acceptable productions of /t/, /s/ and /ʃ/. Some of these patterns are found in both the TD and DS groups but many others are only evident in the DS group, suggesting that children with DS present with more articulation errors than would be identified with auditory analysis.

7. Results part three – Case studies

7.1 Introduction

This chapter presents a detailed discussion on the results from the perceptual, Electropalatography (EPG) and pattern analysis measures, and the factors that may affect them, in five children with Down's syndrome (DS). As children with DS are considered to be variable (and results from Chapter 5 and 6 support this) case studies were included to illustrate the range of abilities found in this group of children with DS in more detail. Results presented in this chapter will help answer all three research questions.

In order to provide a range of speech ability assessed, the results from the standardised speech assessment (DEAP) assessment (see Table 3-1) were consulted and a sample of five participants were selected from the following: the highest and lowest performances on this test, participant scoring closest to the median score, and then two others selected for having scores numerically equidistant to the median and the lowest percent consonant correct (PCC) score and similarly, the median and the highest PCC score. Following these criteria, the participants selected were: DS10, DS24, DS08, DS16, DS23 (see Table 7-1 below for scores).

Child	Chronological age	DEAP PCC	DEAP PVC	RK score	VIQ
DS10	13;10	84%	96%	80%	5;6
DS24	10;5	73%	78%	80%	4;5
DS08	10;2	66%	91%	90%	<4;0
DS16	15;8	40%	72%	68%	<4;1
DS23	17;5	19%	36%	55%	<4;1

Table 7-1: Case study participants. Child: participant code; Chronological age; DEAP PCC: percentage consonant correct score from DEAP assessment; DEAP PVC: percentage vowel correct score from DEAP assessment; RK scores: overall score from Robbins Klee oro-motor assessment; VIQ: verbal intelligence age equivalent score

The following sections will present results from measures for the five case study participants:

Segmental analysis

- Scores from quantitative measures (both perceptual and EPG) and descriptive measures (see Chapter 4) compared to average typically developing (TD) scores.
- EPG patterns for all repetitions of the target sibilants (this will include the whole annotation and a composite pattern of the first frame of maximum contact from those same annotations)
- Alveolar closure score results from the annotations of the target sibilants
- EPG patterns of tokens of target sibilants from DEAP assessment.

Canonical analysis (CA)

- Comparison of individual’s CA scores with training data for target sibilants

Motor and dentition information

- Comparison of individual’s DDK rate and accuracy scores with TD scores
- Dentition information from Orthodontist (if available)

The aim of this section was to further assess the nature of the speech problems in these speakers and relate them to the motor abilities, structural and dentition differences in these speakers (when available). The case study results help to answer RQ1 and RQ2 in more detail. This was also a good opportunity to analyse the relationship between articulatory patterns and perception in detail (RQ3).

7.2 Speaker One: DS10

DS10 is female and was 13;10 years old at the time of initial screening and speech data recording. Her hearing was normal. She presented with a high PCC from the DEAP assessment (84% compared to the average from this group, 62%). Her PVC score from the DEAP was also high: 96% (compared to the average from this group, 83%). Verbal Age equivalent score as measured by Verbal IQ test of the WPPS-II was 5;6 and she scored 80% on the Robbins-Klee oral motor function assessment. She had a Class III dental malocclusion. Her results from the PhD study measures are presented in Table 7-2.

	target sound					
	T		**S**		**ʃ**	
DS10	DS10	**AV. TD**	DS10	**AV. TD**	DS10	**AV. TD**
quantitative measures						
%PTA	100	***100***	100	***93***	70	***91***
COG	4.77	***4.85***	4.17	***4.55***	3.03	***3.64***
Duration(ms)	90	***120***	120	***140***	190	***160***
COV duration	0.35	***0.33***	0.15	***0.16***	0.56	***0.18***
OSvar	12.71	***7.17***	5.37	***7.39***	7.47	***9.39***
PSVar	10.16	***6.46***	5.48	***6.63***	4.84	***8.73***
WTM	0.71	***0.55***	0.3	***0.39***	0.33	***0.41***
descriptive measures						
%typical pattern	80	***91***			40	***59***
%retracted	20	***2***				
%wide groove			100	***8***	30	***7***
%lack of groove					30	***4***

Table 7-2: Perceptual and EPG measures: DS10, PTA: Percentage Target Consonants Acceptable, COG: Centre of Gravity, Duration: length of annotation, COV duration: variability in length of annotation, OSVar: Overall spatial Variability, PSVar: Perceptually acceptable spatial variability, WTM: Whole Total Contact Measure, AV.TD: Average scores from TD group

7.2.1 Segmental analysis

For /t/ and the target fricative sound /s/, there were no perceptual errors. Target /ʃ/ was produced acceptably for 70% of productions. DS10 scores higher than the TD average for perceptual measures of target /s/ (and, at 100%, the same as the TD average for the plosive). The EPG measure results show similar scores and patterns to the TD group, particularly the COG scores with /s/ scoring higher than /ʃ/. DS10 also scores similarly to the TD group in the duration measures and the WTM measures for the fricatives. DS10 shows very similar scores for COV (of duration) for /t/ and /s/ to the TD group, but a higher score for target /ʃ/. The temporal variability pattern is not replicated in the spatial variability. DS10 scores lower for spatial variability than the TD group for the sibilants. DS10 also shows lower variability for the perceptually acceptable tokens for /s/ and /ʃ/. For both OSVar and PSVar, DS10 shows more spatial variability for /t/ than the TD mean value. These scores may reflect the chronological age difference between DS10 (13;10yrs) and the TD group (mean age = 6;1) as we expect less variability in articulation as children mature (though this is in typically developing children, Lee et al. (1999)). It is expected that children with DS are delayed in their speech development and that speech development is not related to cognitive age but there is little research on whether articulation variability changes as the speaker with DS matures (see 8.3.2 for information on age and variability in this study).

A look at the pattern types for the target fricatives shows that the typical pattern was not consistently used. For /s/ all of the productions were considered to be produced with a wide groove. For /ʃ/, 40% of the productions were made with the standard pattern but 30% were reported to be produced with a wide groove and 30% were lacking a groove. Both these patterns are found in the typical developing group and are reported in studies of typical adult /s/ and /ʃ/.

7.2.1.1 /s/ EPG patterns

The EPG patterns for each repetition of target /s/ are presented in Figure 7-1 below. DS10 displays a similar articulation pattern for all productions of target /s/ (i.e. a groove at the alveolar place of articulation). They are all identified as wide groove (4 electrodes or more) articulations with some repetitions showing a narrowing of the groove in the middle of the annotation (for example, repetitions 3, 4 and 10) which is similar to the adult standard pattern of articulation. This dynamic change of the groove width is further investigated in Figure 7-2 below.

All productions of target /s/ are perceived as acceptable [s] productions suggesting that the wide groove width used by DS10 does not impact perceptual acceptability. The variation of groove width can be seen in Figure 7-2 below which shows the anterior closure measure from all productions of /s/. The majority of productions follow a similar pattern to the average AD groove width across the annotation (with a narrowing of the groove at the middle of the articulation).

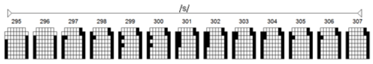
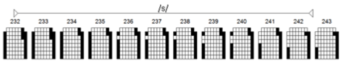
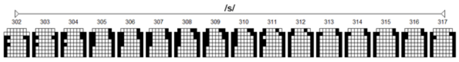
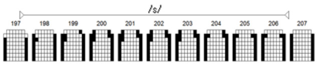
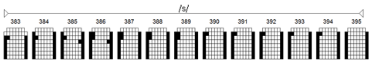
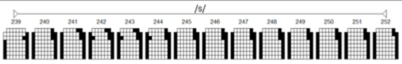
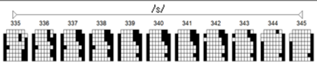
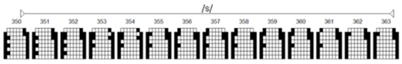
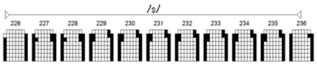
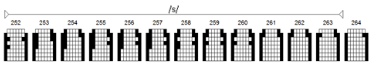
		Pattern Type	Transcription
1		wide groove	[s]
2		wide groove	[s]
3		wide groove	[s]
4		wide groove	[s]
5		wide groove	[s]
6		wide groove	[s]
7		wide groove	[s]
8		wide groove	[s]
9		wide groove	[s]
10		wide groove	[s]

Figure 7-1: Lingual palatal EPG contacts for all ten productions of target /s/ from 'a sun' for DS10. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-2 below.

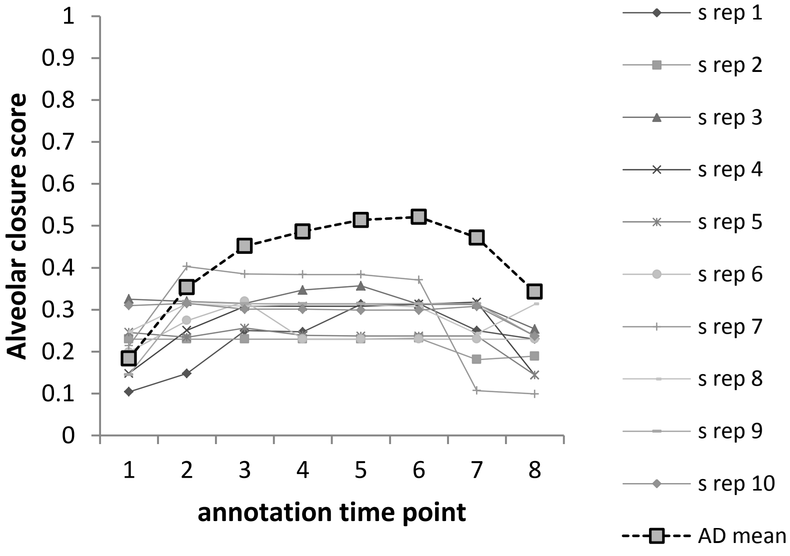


Figure 7-2: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /s/ in 'a sun': DS10. DS10 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /s/ in 'a sun'.

The composite pattern in Figure 7-3 below confirms that DS10 manages lateral contact for the maximum frame of constriction in all productions of target /s/. The groove width is never narrower than 3 electrodes, though at times expands to 4 or 5.

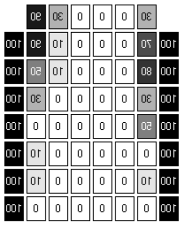


Figure 7-3: Single average frame of maximum contact from all repetitions of /s/, DS10 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

The tokens of target /s/ from the DEAP assessment are presented in Figure 7-4. Both WI and WF /s/ productions confirm the patterns identified in the repetition data.

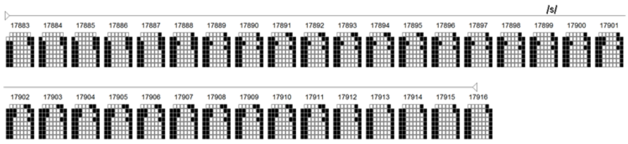
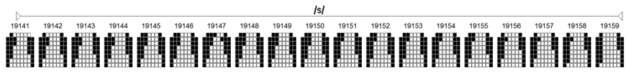
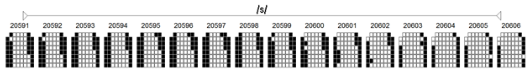
		Pattern Type	Transcription
scissors		wide groove	[s]
lighthouse		typical pattern	[s]
sausage		wide groove	[θ]

Figure 7-4: Lingual palatal EPG contacts for all productions of target /s/ from DEAP phonology assessment for DS10. Descriptive patterns types presented alongside agreed perceptual transcription.

7.2.1.2 /ʃ/ EPG patterns

Figure 7-5: below shows that DS10 was heard as producing mostly acceptable productions of /ʃ/, and managed to create a channel for central airflow for all productions. The one error, [s], presents with a typical post-alveolar pattern. There appears to be no relationship between the pattern identified and the perceptual analysis but the transcription presented is broad and may obscure fine phonetic differences (e.g. lack of lip rounding).

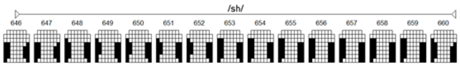
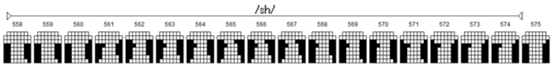
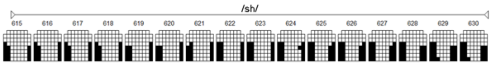
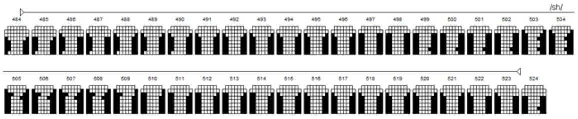
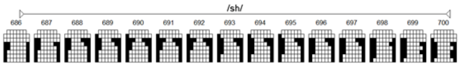
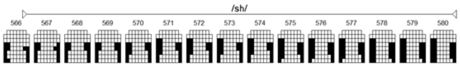
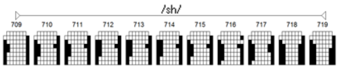
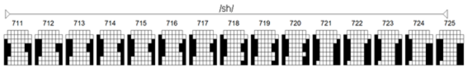
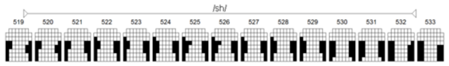
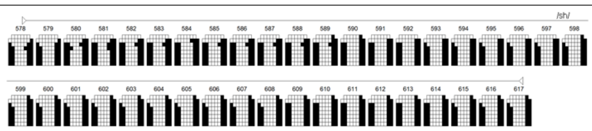
		Pattern Type	Transcription
1		lack of groove	[ʃ]
2		typical pattern	[s]
3		lack of groove	[ʃ]
4		lack of groove	[ʃ]
5		typical pattern	[ʃ]
6		wide groove	[ʃ]
7		wide groove	[ʃ]
8		wide groove	[ʃ]
9		typical pattern	[ʃ]
10		typical pattern	[ʃ]

Figure 7-5: Lingual palatal EPG contacts for all ten productions of target /ʃ/ from 'a sheep' for DS10. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-7 below.

As shown in the composite frame (Figure 7-6), all the EPG patterns have presence of lateral bracing and a central groove (between 2-4 electrodes wide). The groove pattern is varied throughout but, as reflected in the COG measurements, the articulation of target /ʃ/ is more retracted than target /s/ production. These findings suggest that groove width for DS10 does not impact on perceptually acceptability of /ʃ/.

	0	0	0	0	0	0	
30	0	0	0	0	0	10	30
80	70	10	0	0	20	40	60
100	100	20	0	0	10	80	100
100	100	0	0	0	0	90	100
100	90	0	0	0	0	90	100
100	90	0	0	0	10	90	100
100	70	0	0	0	0	70	100

Figure 7-6: Single average frame of maximum contact from all repetitions of /ʃ/, DS10 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

Figure 7-7: presents the alveolar closure scores from 8 equally spaced points across the /ʃ/ productions. As expected (from Figure 7-5:) the groove widths are varied for the productions, some show more narrowing near the midpoint of the production, though others show a more consistent wide groove pattern. For the narrower grooved articulations DS10 shows a widening of the groove near the end of the friction portion. As shown in the mean AD alveolar closure scores, typically in the word ‘sheep’ the groove pattern may not alter (or is widened only slightly) at the end of the fricative due to the pattern associated with the /i/ vowel. DS10 produced variable vowel qualities in her productions of ‘sheep’. Seven of the productions contain an [i] vowel, a lowered [i̞] vowel is produced in repetitions 2 and 8, and in repetition 7 she produces a [ɪ] vowel.

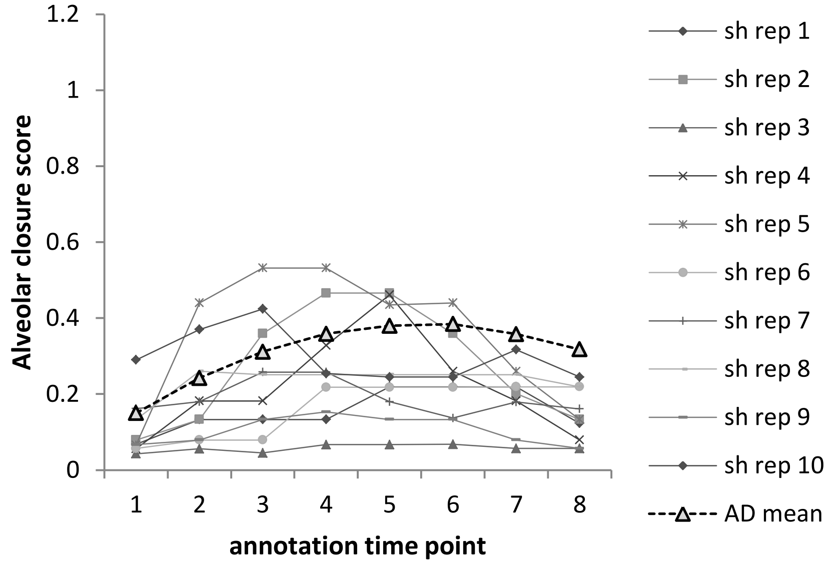


Figure 7-7: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /ʃ/ in ‘a sheep’: DS10. DS10 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /ʃ/ in ‘a sheep’.

The DEAP data in Figure 7-8 confirms that DS10 can achieve the correct lingual-palatal constriction for production of target /ʃ/. The patterns may show wider grooving than in adult productions but she manages to create a central airflow with lateral bracing evident at the post-alveolar region.

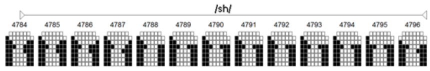
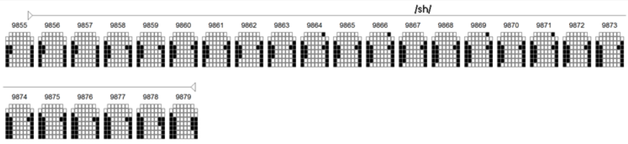
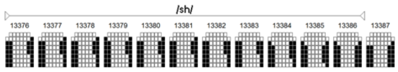
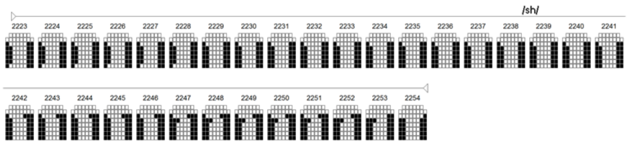
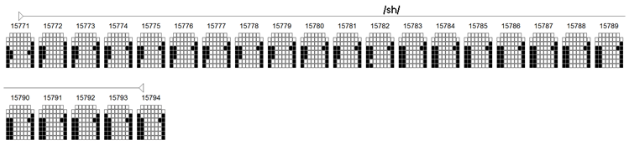
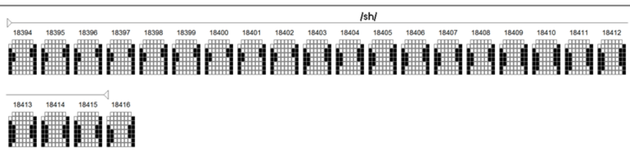
		Pattern Type	Transcription
sheep		typical pattern	[ʃ]
splash		wide groove	[ʃ]
sheep		wide groove	[ʃ]
fish		lack of groove	[ʃ]
toothbrush		wide groove	[ʃ]
fishing		wide groove	[ʃ]

Figure 7-8: Lingual palatal EPG contacts for all productions of target /ʃ/ from DEAP phonology assessment for DS10. Descriptive patterns types presented alongside agreed perceptual transcription.

7.2.2 Canonical Analysis

The CA chart for /s/ below shows that the spatial patterns sit close to the alveolar place of articulation, overlapping the space for AD /t/ and /s/. The CA scores indicate that for all productions of /s/, DS10 has the correct place of articulation (and is not retracting into the post-alveolar region) sharing some features with AD /t/ production. In Figure 7-9 the attempted productions of /s/ are shown by ∇, and the variation is represented by blue ellipses (1 & 2 standard deviations).

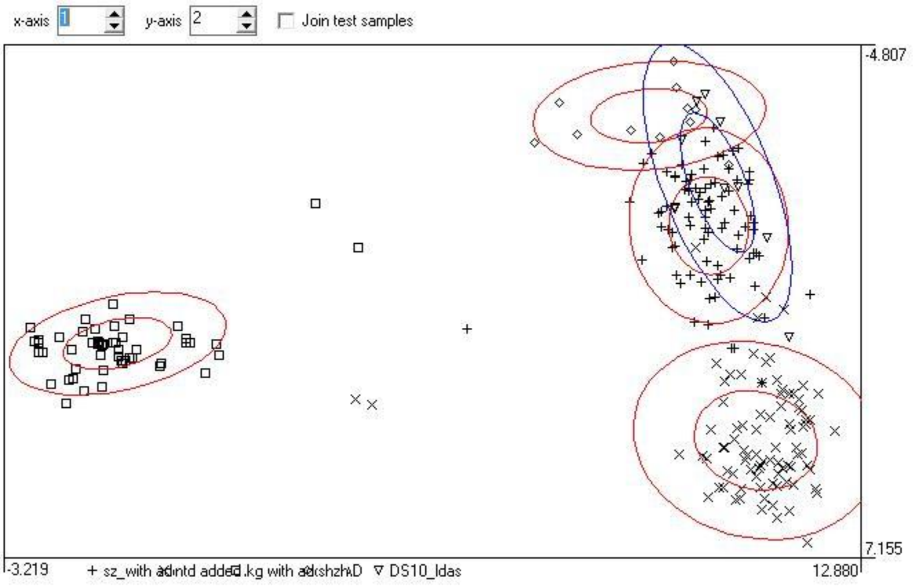


Figure 7-9: CA chart of DS10 target /s/ (∇) productions compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns

The CA chart (Figure 7-10) for target /ʃ/ (∇) shows a much wider spread with articulations spreading across the /t/ and /s/ spaces, with some nearing the /k/ space. There are no productions that fit into the space set by the AD /ʃ/ training productions though some show a positioning towards the articulation space for /k/, reflecting a more posterior articulation than for /s/ productions.

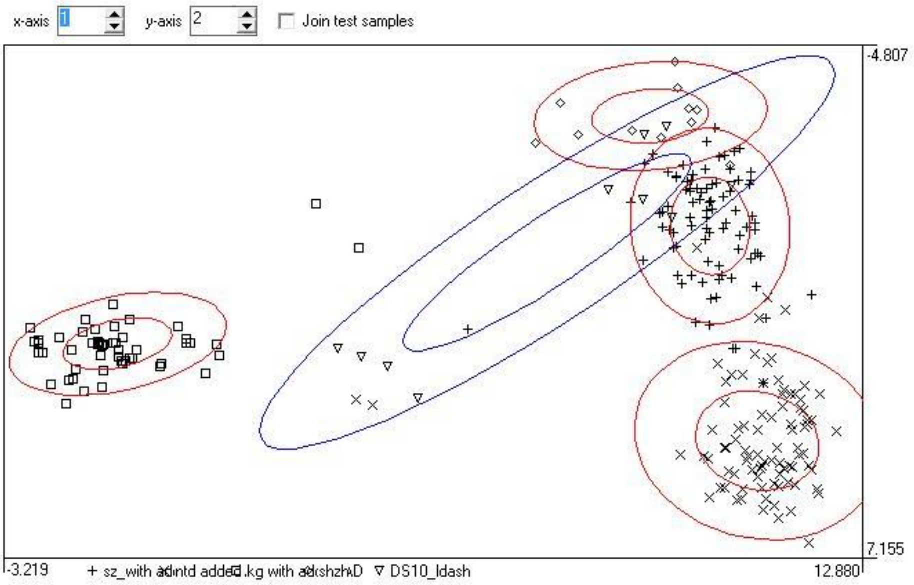


Figure 7-10: CA chart of DS10 target /ʃ/ (∇) productions compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns

7.2.3 Motor ability and dentition

DS10 scored 80% on the Robbins-Klee oral function task and has a low variability score from the articulation measures, therefore her speech motor control skills present at a high level in comparison to the other participants with DS. Her DDK rate and accuracy scores are presented in Table 7-3 below along with mean TD scores.

	DDK rate and accuracy									
	p		**t**		**k**		**tk**		**ptk**	
	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %
DS10	6.48	33.3	5.61	100	5.07	100	3.73	66.7	3.28	33.3
TD	*4.92*	*89.6*	*4.72*	*93.8*	*4.22*	*97.9*	*4.84*	*87.5*	*3.96*	*62.5*

Table 7-3: Mean DDK rate (syllables per second) and accuracy (% acceptable) for repetitions of /pə/, /tə/, /kə/, /təkə/ and /pətəkə/ by DS10, presented alongside the TD group mean scores

DS10 shows a faster rate for monosyllabic DDK productions when compared with TD norms. The di- and tri-syllabic productions are slightly slower. Therefore, as evidenced from these TD DDK rates, DS10 presents with normal speech motor abilities. Accuracy is high for the lingual monosyllabic productions but she has accuracy difficulties for repetitions of labial syllables (also reflected in the trisyllabic sequence), which presents a more atypical picture.

DS10 had a Class III malocclusion which presents as a protruded mandible and has been associated with a flaccid, lower tongue position (Johnson & Sandy, 1999), and related to misarticulations of /s/ (Guay et al., 1978). Guay et al (1978) found that speakers with Class III malocclusions produced /s/ in a retracted tongue position which they suggested compensated for the dental malocclusion. However, the data presented here shows that DS10 has no obvious difficulties with tongue precision at the alveolar place of articulation. Dentition differences have also not impacted on the participant’s ability to create successful friction of the alveolar fricative.

7.2.4 DS10 Summary

Overall DS10 presents as a typically developing child with little problems with production of voiceless sibilants or WI /t/. When compared with cognitively matched TD children she shows fewer perceptual errors than the TD average and a lower variability score for sibilant production. EPG measures show that she does not present with any significant differences in comparison with the TD group scores for COG and WTM. Descriptive analysis of articulation patterns show that DS10 produces a groove constriction for both target sibilants but groove width is wider than TD and AD productions. However, differences are noted in the DDK task with lower than typical accuracy scores for labial segment repetitions.

7.3 Speaker Two: DS24

DS24 is male and was 10;5 at the time of initial screening and speech recording. He presented with a mild conductive hearing loss. His DEAP PCC score was higher than average for the DS group, with a PCC score of 73% but the PVC score (78%) was slightly lower than the average group score. His Verbal Age Equivalent was 4;5 and he scored 80.77 on the Robbins-Klee oral motor function assessment. His results from the PhD study measures are presented in Table 7-4 below.

7.3.1 Segmental analysis

DS24 displays an atypical production pattern for the target sounds /t/, /s/ and /ʃ/. Perceptually he produces three acceptable productions for target /t/ (errors include [p̃ʰ], [z̃], [ts], [ɬt], [s], [z] and [ç]). This variability may indicate particular difficulties with speech motor control in this speaker, particularly affecting the control of the velum resulting in high levels of nasal airflow. This will be further assessed in the EPG data for /s/ and /ʃ/ below. The production of /s/ is more successful with 60% acceptable productions, though only errors are produced for /ʃ/. The EPG measures do not show many differences with the TD group for the 3 target sounds. COG scores are similar to TD scores, though target /t/ scores slightly lower than the TD COG score and his own scores for target /s/. He achieves the acceptable directional difference between the COG scores for /s/ and /ʃ/ (indicating that overall his production of /s/ is more anterior than productions of /ʃ/ and suggesting that he is aiming for a different target sound), though these are slightly closer together than the TD scores. His duration scores look similar to the TD means, though the COV measure of duration for all target sounds appear higher, suggesting more variability.

	target sound					
	t		s		ʃ	
DS24	DS24	**AV. TD**	DS24	**AV. TD**	DS24	**AV. TD**
quantitative measures						
%PTA	30	***100***	60	***93***	0	***91***
COG	4.15	***4.85***	4.59	***4.55***	3.9	***3.64***
Duration	200	***120***	110	***140***	100	***160***
COV duration	0.5	***0.33***	0.4	***0.16***	0.26	***0.18***
OSvar	13.23	***7.17***	12.58	***7.39***	5.48	***9.39***
PSVar	4.83	***6.46***	10.75	**6.63**	-	***8.73***
WTM	0.77	***0.55***	0.62	***0.39***	0.89	***0.41***
descriptive measures						
%typical pattern	40	***91***	20	***79***		
%full anterior closure	30	***0***				
%lack of lateral contact	10	***0***				
%complete alveolar closure			60	***2***		
%double articulation			10	***0***		
%undifferentiated gesture	20	***0***	10	***0***	90	***0***
%articulatory drift					10	***0***

Table 7-4: Perceptual and EPG measures: DS24, PTA: Percentage Target Consonants Acceptable, COG: Centre of Gravity, Duration: length of annotation, COV duration: variability in length of annotation, OSVar: Overall spatial Variability, PSVar: Perceptually acceptable spatial variability, WTM: Whole Total Contact Measure, AV.TD: Average scores from TD group

The OSVar scores are higher than the TD average for /t/ and /s/ (almost double the TD mean score for /t/). After removal of the productions judged perceptually as inacceptable, DS24's variability scores are lower. Nevertheless, he is still more variable than the TD group mean for /s/ production, though the revised score for /t/ productions is within normal limits. The WTM score is higher for all 3 target sounds but particularly so for target /ʃ/.

The pattern analysis for DS24 illustrates the variability of articulation that this speaker displays. /t/ patterns are mostly identified as *full anterior closure* or *typical pattern*. Only 30% of the articulations are heard as perceptually acceptable but 40% of the patterns appear to be typical which may reflect a lateralised production.

7.3.1.1 /s/ EPG analysis

Figure 7-11 shows that the articulation patterns of /s/ were prominently the *complete alveolar closure* pattern, variably perceived to be [t], [ɬs], [ts] and [s]. DS24 shows patterns classified as *typical alveolar fricative pattern, undifferentiated gesture* and *double articulation* (which also involves a complete closure at the alveolar region).

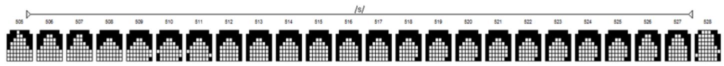
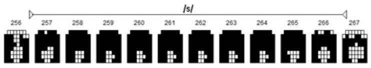
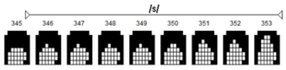
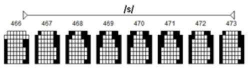
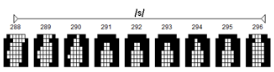
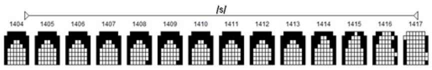
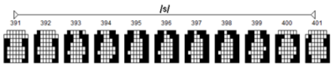
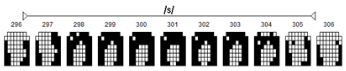
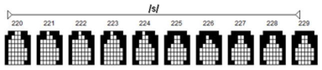
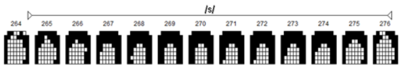
		Pattern Type	Transcription
1		complete alveolar closure	[t]
2		undifferentiated gesture	[z]
3		complete alveolar closure	[ts]
4		typical pattern	[s]
5		complete alveolar closure	[s]
6		complete alveolar closure	[ɬs]
7		typical pattern	[s]
8		double articulation	[s]
9		complete alveolar closure	[s]
10		complete alveolar closure	[s]

Figure 7-11: Lingual palatal EPG contacts for all ten productions of target /s/ from 'a sun' for DS24. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-13 below.

The articulation patterns for target /s/ are variable but all show anterior contact (with at times some velar constriction). The composite frame in shows constant lateral contact from row 8 through to row 1 on the frame but with varies between complete and incomplete contact across the alveolar rows (1-3), suggesting a difficulty maintaining the narrow groove articulation. When DS24 produces a groove it is very narrow (compared to others in the DS group) but this is not consistent.

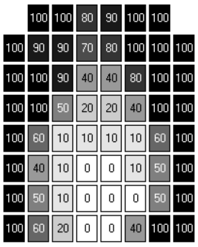


Figure 7-12: Single average frame of maximum contact from all repetitions of /s/, DS24 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact)

DS24's attempts at /s/ production indicate presence of tongue tip/blade control, but he is possibly lacking the motor skills to create a stable groove constriction. Many of the lingual-palatal patterns in Figure 7-11 present with complete closure at the anterior section of the palate and often these were perceived to be acceptable productions of target /s/. Complete alveolar closure has been noted for fricative production in studies of typical children and adults with McLeod et al. (2006) suggesting that friction is produced through a narrow gap between electrodes. However, the amount of contact produced in some of these tokens does not lend itself to McLeod et al.'s theory. In this case, it may be that DS24 is producing friction which is released posterior to the EPG palate. For friction to escape this way, it would usually have to take the form of a lateral or nasal release (Gibbon, 2004). However, only repetition 6 was heard to have any presence of lateral friction during the production. These findings may be somewhat limited by the broad transcription and the lack of acoustic analysis. Further investigations are required to confidently interpret the nature of the sibilant articulation in this speaker.

The alveolar closure scores (Figure 7-13) from target /s/ production show a narrowing of groove across the productions, followed by a widening at the end of the fricative portion. The high numbers for DS24 reflect the complete closure that DS24 produces for target /s/. The dynamic patterns for /s/ production present both between- and within-articulation variability.

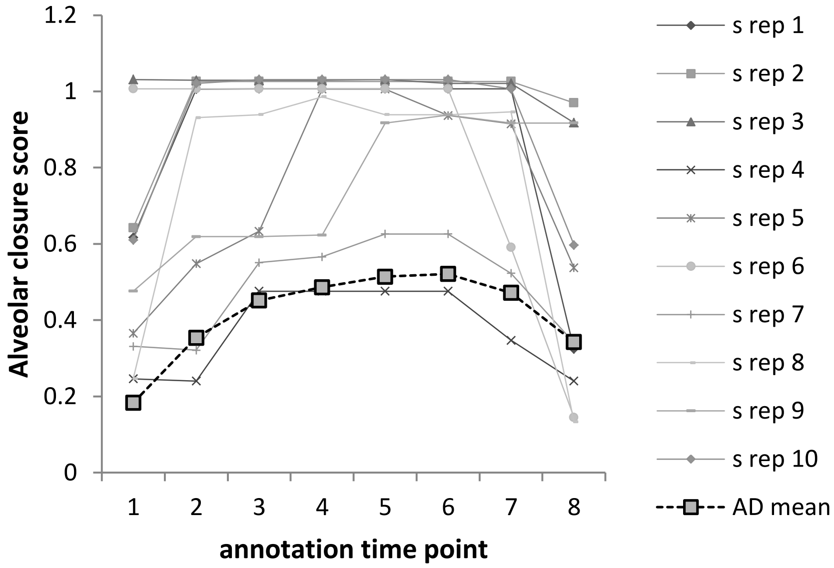


Figure 7-13: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /s/ in ‘a sun’: DS24. DS24 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /s/ in ‘a sun’.

The target /s/ productions from the DEAP assessment in Figure 7-14 provide more detail about the articulatory variability DS24 displays in target /s/ production. WF /s/ is particularly problematic for DS24 with productions being transcribed as velopharyngeal fricatives. Perceptually he achieves a fricative production in WI position but the placement (and direction of airflow) is incorrect. The articulation of *lighthouse* was particularly difficult to categorise, it could possibly be classified as *double articulation.* The data in Figure 7-14 present a wider range of articulations for DS24 compared to the repetition data in Figure 7-11. This may be related to the word position (e.g. *house, lighthouse*) but it may also be related to then data elicitation method. The two types of data elicitation are very different tasks, with one (DEAP) being a lengthy activity compared to the relative short (and by nature repetitive) activity of the word list repetitions. Speech elicited from the standardised assessment may be subject to participant tiredness and motivation with the task, this has the potential to affect rate and accuracy of speech during recordings.

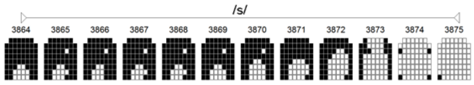
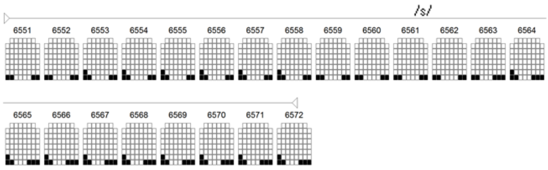
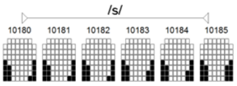
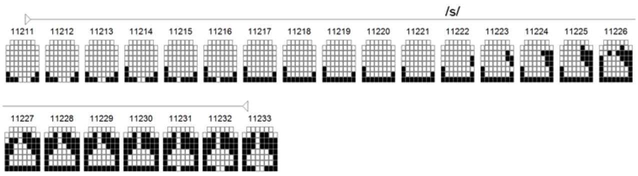
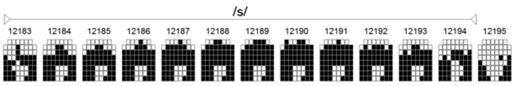
		Pattern Type	Transcription
sock		complete alveolar closure	[ʪ]
house		minimal contact	[fŋ]
scissors		velar constriction with lateral contact	[h]
lighthouse		velar constriction with lateral contact	[fŋ]
sausage		double articulation	[ɬ]

Figure 7-14: Lingual palatal EPG contacts for all productions of target /s/ from DEAP phonology assessment for DS24. Descriptive patterns types presented alongside agreed perceptual transcription.

7.3.1.2 /ʃ/ EPG patterns

The precise articulation required for target /ʃ/ is never achieved in this series of repetitions for DS24 (Table 7-10). There is a larger than usual amount of tongue-palate contact for the production of these sounds. The main pattern used here is *undifferentiated gesture* which may suggest a deficit in oral motor control ability (Gibbon, 1999). As shown above, there is a lack of tongue tip-body distinction in the production of target /ʃ/ resulting in atypical articulations for all attempted productions. There is a range of perceptual variability for /ʃ/ and no relationship between the perceptual analysis and the articulation patterns. DS24 is heard as producing [ɬ], [ɮ] and [h], though with similar articulation patterns. In the case of the lateral fricatives, it may be that the airflow is escaping laterally behind the molars (thus behind the reach of the EPG palate), this may also be the case for the [h] productions.

The alveolar closure scores for target /ʃ/ productions (Figure 7-16 below) are very unlike patterns for the mean adult /ʃ/ productions. The scores are high, reflecting complete closure across the palate, except in two of the productions (repetitions 5 and 8 which do not show complete alveolar closure throughout the whole annotation).

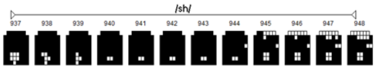
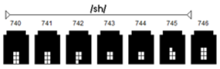
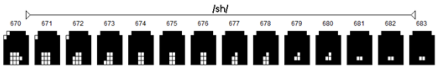
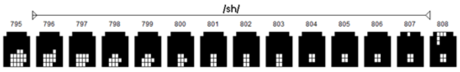
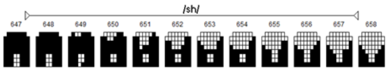
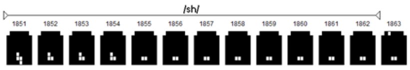
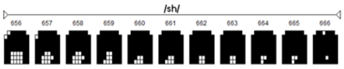
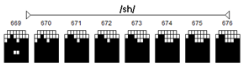
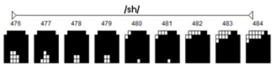
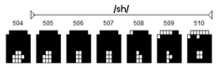
		Pattern Type	Transcription
1		undifferentiated gesture	[h]
2		undifferentiated gesture	[h]
3		undifferentiated gesture	[h]
4		undifferentiated gesture	[h]
5		articulatory drift	[ɬ]
6		undifferentiated gesture	[ɮ]
7		undifferentiated gesture	[h]
8		undifferentiated gesture	[h]
9		undifferentiated gesture	[h]
10		undifferentiated gesture	[ɬ]

Figure 7-15: Lingual palatal EPG contacts for all ten productions of target /ʃ/ from 'a sheep' for DS24. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-16 below.

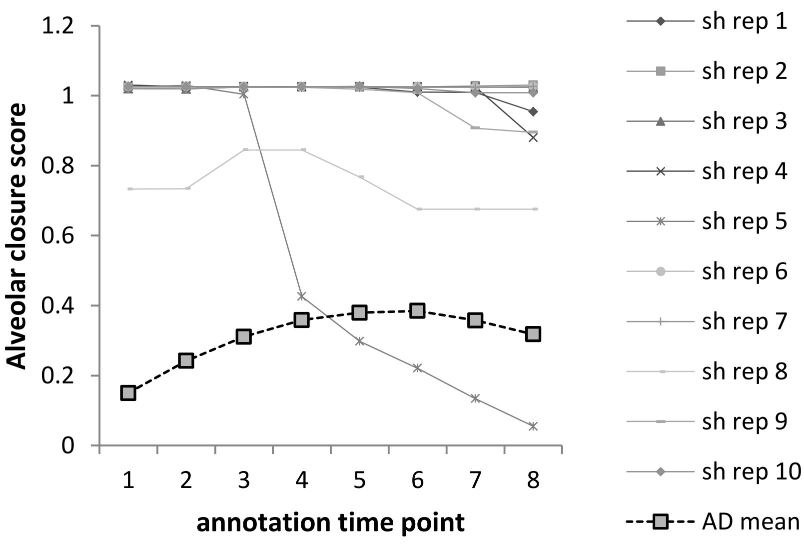


Figure 7-16: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /ʃ/ in 'a sheep': DS24. DS24 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /ʃ/ in 'a sheep'.

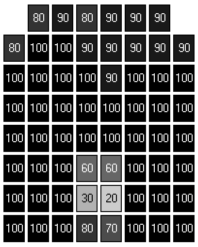


Figure 7-17: Single average frame of maximum contact from all repetitions of /ʃ/, DS24 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact)

The variability in production of target /ʃ/ is represented by a single composite frame in Figure 7-12. This does not represent the dynamic changes in articulation but clearly shows the, almost, complete palatal contact used for target /ʃ/.

The EPG patterns from the DEAP words (Figure 7-18) present with *undifferentiated gestures* for all productions, with the majority perceived as lateral fricatives. Similar to the repetition data, in all cases DS24 presents with high levels of lingual-palatal.

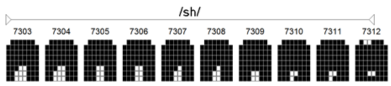
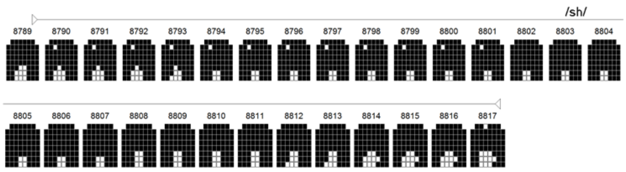
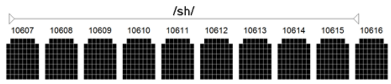
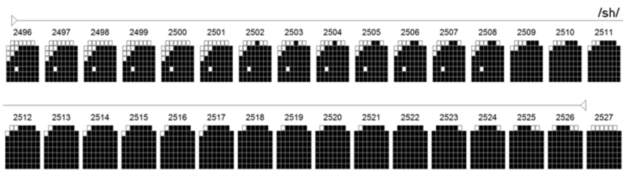
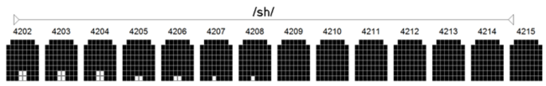
		Pattern Type	Transcription
sheep		undifferentiated gesture	[ɬ]
toothbrush		undifferentiated gesture	[ɬ]
fishing		undifferentiated gesture	[h]
fish		undifferentiated gesture	[ɬ]
sheep		undifferentiated gesture	[ɬ]

Figure 7-18: Lingual palatal EPG contacts for all productions of target /ʃ/ from DEAP phonology assessment for DS24. Descriptive patterns types presented alongside agreed perceptual transcription.

7.3.2 Canonical Analysis

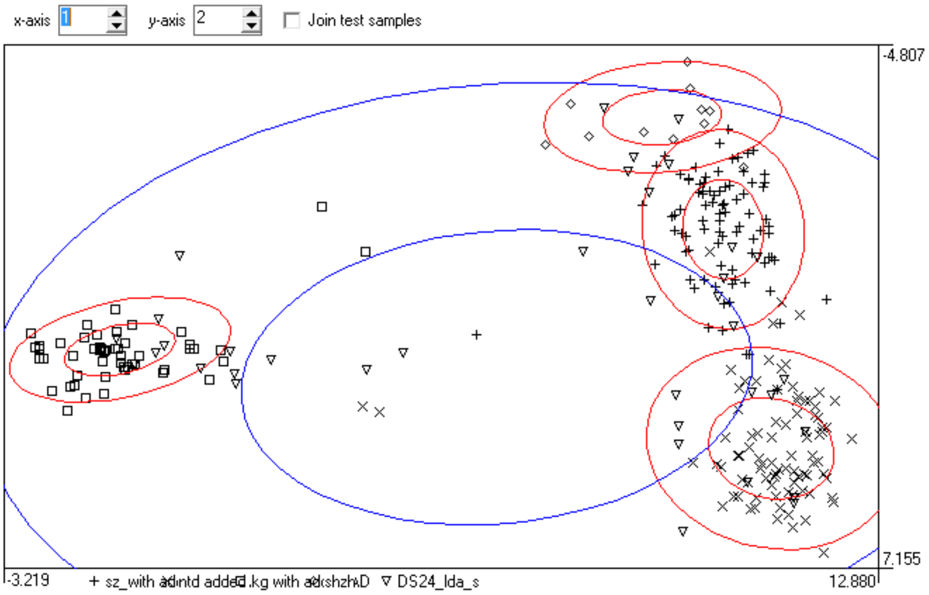


Figure 7-19: CA chart of target /s/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS24

The canonical analysis for /s/ production (in Figure 7-19) shows a wide articulation area which shows similarities to all articulations in the reference set.

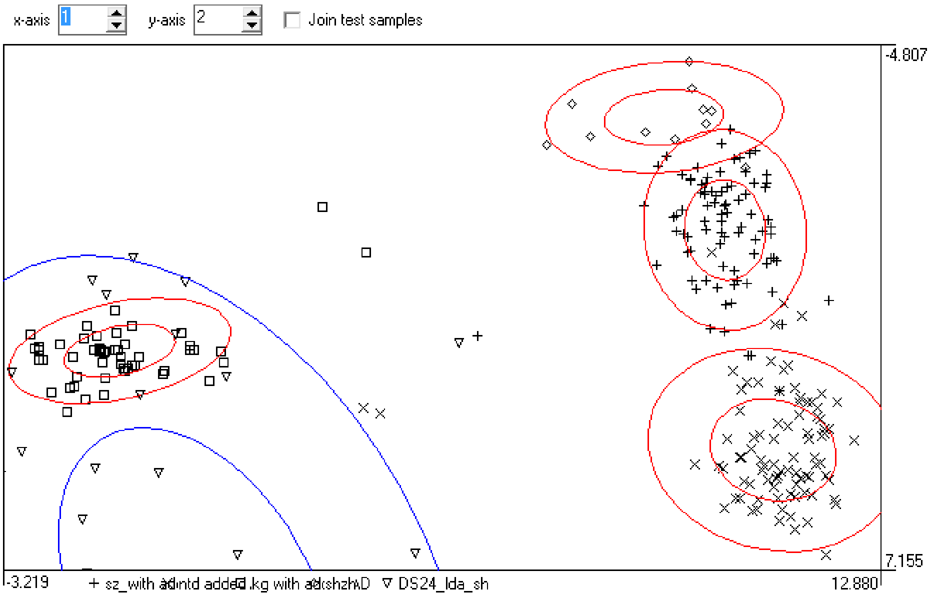


Figure 7-20: CA chart of target /ʃ/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS 24

Figure 7-20 presents a different pattern of articulation for the CA scores of /ʃ/. The articulations show more posterior articulations than the /s/ productions above, with most productions identified as being similar to the /k/ articulatory space.

7.3.3 Motor ability and dentition

It is evident from the articulation patterns above that DS24 has difficulty creating the distinct groove articulation pattern for post-alveolar fricative production, however, the RK function measure found DS24 to perform similarly to DS10 above (who does not show similar problems), this may reflect the limitations of the RK measure (which is a non-speech oromotor measure rather than a speech motor task).

DDK rate and accuracy

	p		**t**		**k**		**tk**		**ptk**	
	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %
DS24	5.62	50	4.10	33.3	3.57	50	2.26	16.70	1.73	0
TD	*4.92*	*89.6*	*4.72*	*93.8*	*4.22*	*97.9*	*4.84*	*87.5*	*3.96*	*62.5*

Table 7-5: Mean DDK rate (syllables per second) and accuracy (% acceptable) for repetitions of /pə/, /tə/, /kə/, /təkə/ and /pətəkə/ by DS24, presented alongside the TD group mean scores

DS24 shows normal DDK scores for the monosyllabic tasks but a lower rate for the multisyllabic tasks. Accuracy is low across all tasks but particularly in the /ptk/ repetitions. His DDK score was 1.73 for the trisyllabic repetition, which is much lower than the TD norms from this study. Thoonen et al. (1996) note that speakers with CAS present with difficulties in the trisyllabic DDK tasks, while performing as typical speakers in the monosyllabic tasks. These results suggest that DS24 shows signs of motor difficulties similar to children with CAS.

7.3.4 DS24 Summary

DS24 scored 73% for PTA in the DEAP phonology assessment and closer analysis of the PTC scores for /t/, /s/ and /ʃ/ found low scores for all three. This speaker's perceptual measures present as atypical, relating to the higher incidence of errors in /t/ than /s/. The EPG pattern analysis found that the articulation patterns used by this speaker were also atypical. This was most evident in the production of target /ʃ/ but DS24 uses atypical articulation patterns for all 3 target sounds (i.e. not used in the TD data). However, although the agreed transcription found repetitions of target /s/ to be perceptually inacceptable (voicing and tongue shape errors only), DS24 is able to create an alveolar articulation for target /s/. Evidence from only target /ʃ/ would suggest that DS24 has problems with the independent control of the tongue top/blade and the tongue body (Gibbon, 1999), however the patterns identified for target /s/ would suggest not. The patterns and COG scores suggest that DS24 is attempting to produce two different target sounds for the sibilants but /ʃ/ proves to be a more complicated articulation. The differences between the alveolar and post-alveolar targets may be related to coarticulatory effects of the front high vowel following target /ʃ/, however this pattern is also noted for the DEAP words which involve a variety of vowel contexts. Further investigation of the acoustic pattern of these productions could provide information on additional articulations involved in these productions, for example, establish the nature of the friction (e.g. lateral or nasal) that the speaker produces for sibilant production. DS24 also presents with a mild conductive hearing loss. Although no causal link can be suggested, it may be proposed that the lack of auditory feedback would have an impact on successful production of sibilants in this speaker.

The DDK tasks reveal difficulties with trisyllabic repetitions which may suggest presence of apraxia in this speaker.

7.4 Speaker Three: DS08

DS08 is male and was 10;2 years old at the time of initial screening and speech data recording. His hearing was aided to within normal limits. He presented with an average percentage of consonants correct score from the DEAP assessment (66% compared to the average from this group, 62%). His score of vowel productions from the DEAP was higher: 91% (compared to the average from this group, 83%). Verbal Age equivalent score was <4;0 and he scored 90% on the Robbins-Klee oral motor function assessment. He had a Class I malocclusion. His results from the PhD study measures are presented in Table 7-6.

	target sound					
	t		s		ʃ	
DS08	DS08	**AV. TD**	DS08	**AV. TD**	DS08	**AV. TD**
quantitative measures						
%PTA	87.5	***100***	88.9	***93***	40	***91***
COG	4.3	***4.85***	4.31	***4.55***	4.18	***3.64***
Duration(ms)	200	***120***	170	***140***	160	***160***
COV of duration	0.43	***0.33***	0.35	***0.16***	0.54	***0.18***
OSvar	6.65	***7.17***	12.72	***7.39***	11.13	***9.39***
PSVar	6.65	***6.46***	11.45	***6.63***	9.14	***8.73***
WTM	0.84	***0.55***	0.49	***0.39***	0.46	***0.41***
descriptive measures						
%typical pattern	38	***91***	66	***79***		
%full anterior contact	25	***1***				
%double articulation	13	***1***	11	***33***	10	***0***
%undifferentiated gesture	25	***0***				
%complete alveolar			22	***0***	20	***0***
%fronted groove					60	***14***
%affricate					10	***1***

Table 7-6: **Perceptual and EPG measures: DS08, PTA: Percentage Target Consonants Acceptable, COG: Centre of Gravity, Duration: length of annotation, COV duration: variability in length of annotation, OSVar: Overall spatial Variability, PSVar: Perceptually acceptable spatial variability, WTM: Whole Total Contact Measure, AV.TD: Average scores from TD group**

7.4.1 Segment production

DS08 does not produce any target sound without error, though in the case of target /t/ and /s/, only one repetition was in error. The production of /ʃ/ however was less successful with only 4/10 productions considered perceptually acceptable. The COG scores for DS08 show the acceptable pattern (/t/ and /s/ higher than /ʃ/) but they are less distinct compared to the TD group. The COG values for /s/ averaged close to TD scores but /ʃ/ is produced further forward than the TD average. As presented below, DS08 uses unusual, highly asymmetrical patterns which may have an impact on COG scores. DS08 was more variable in his production of the target fricatives compared to the TD average OSVar scores. The PSVar scores show that this difference remains, with a large difference for perceptually acceptable /s/. DS08 shows increased contact for /t/ production (WTM score) and presents with high spatial and temporal variability (for the sibilants).

7.4.1.1 /s/ EPG patterns

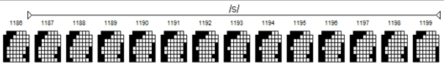
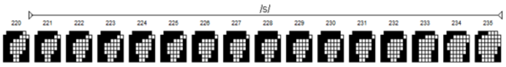
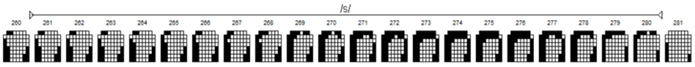
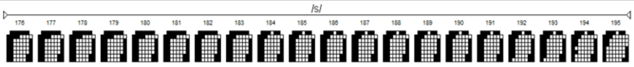
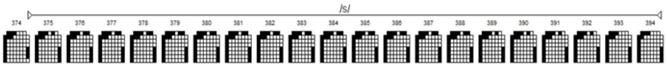
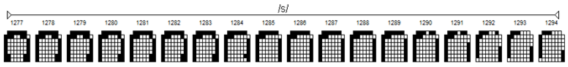
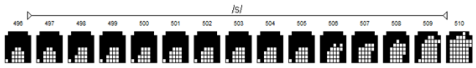
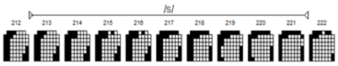
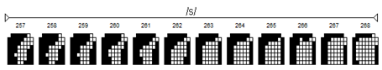
		Pattern Type	Transcription
1		typical pattern	[s]
2		double articulation	[s]
3		typical pattern	[ls]
4		typical pattern	[s]
5		typical pattern	[s]
6		complete alveolar closure	[s]
7			
8		complete alveolar closure	[s]
9		typical pattern	[s]
10		typical pattern	[s]

Figure 7-21: Lingual palatal EPG contacts for all ten productions of target /s/ from 'a sun' for DS08. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-22 below.

The descriptive pattern analysis found that the majority of /s/ productions were produced with a typical fricative pattern, but not as many as would be expected considering the high PTA score for /s/. DS08 also produced a double articulation pattern and complete alveolar closure. Figure 7-21 above shows *typical pattern, double articulation,* and *complete alveolar closure* perceived as perceptually acceptable. His articulation of target /s/ is very asymmetrical, making the pattern analysis harder to complete. It may be incorrect to classify the patterns above as typical as the groove width is difficult to distinguish. However, the patterns are analysed with regard to the presence of a groove. There are a number of tokens in which the tongue's rightward asymmetry is particularly prominent. Repetition 3 was particularly difficult to categorise as it presents as a wide groove that narrows almost to the point of closure. Further comparable examples follow.

Figure 7-22 below presents the alveolar closure scores for DS08's productions of target /s/. These patterns are very different to those seen in DS10 and DS24 and very varied. The alveolar closure score is designed to calculate contact across the front of the palate, the high scores below are related to the complete contact across the first row of the palate evidenced in many productions of target /s/.

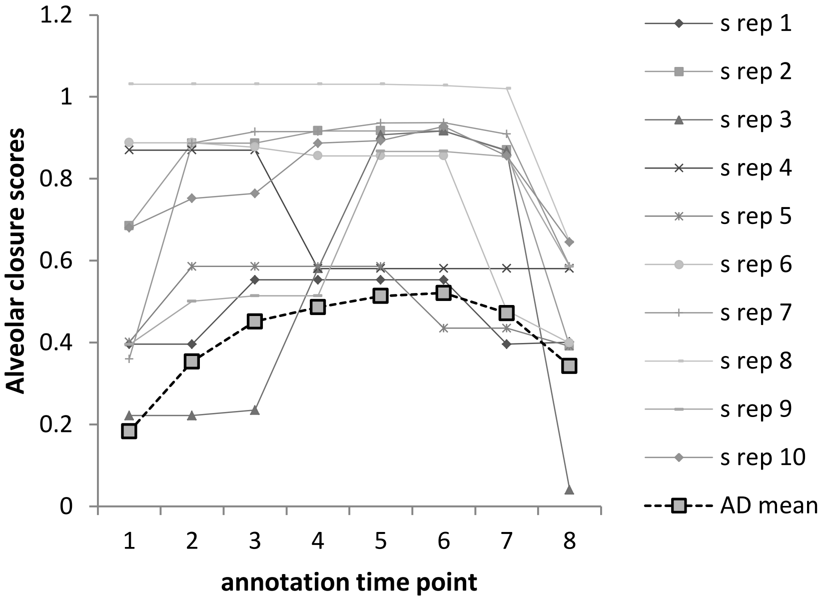


Figure 7-22: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /s/ in 'a sun': DS08. DS08 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /ʃ/ in 'a sheep'.

DS08 consistently produces lingual contact with the sides of the palate, continuing through to row 1 on the left side (and to the middle of this row) for all productions of /s/ and this is reflected in the alveolar closure scores in Figure 7-22. The alveolar closure measure reflects the contact across the first row of electrodes. As this is continuous, the closure score is high for many of DS08's productions of /s/.

The composite pattern in Figure 7-23 shows the tendency of DS08 to produce target /s/ with a rightwards asymmetry. The groove width (0-3 electrodes) varies across the top right of the palate.

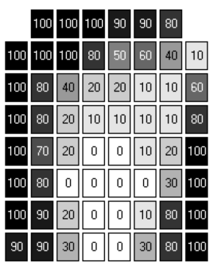


Figure 7-23: Single average frame of maximum contact from all repetitions of /s/, DS08 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

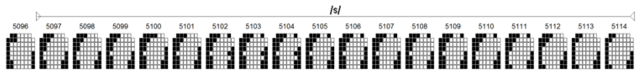
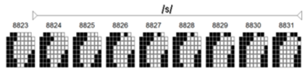
		Pattern Type	Transcription
sock		retracted pattern	[ʃ]
house		retracted pattern	[s]

Figure 7-24: Lingual palatal EPG contacts for all productions of target /s/ from DEAP phonology assessment for DS08. Descriptive patterns types presented alongside agreed perceptual transcription.

The /s/ patterns analysed from the DEAP show a similar pattern to the repetition data in Figure 7-24. The articulation is often asymmetrical with lateral grooving (to the right) in both WI and WF position, however groove width presents as wider in these examples.

7.4.1.2 /ʃ/ pattern analysis

DS08 used the fronted groove pattern (suggesting a /s/-like production) for 6 productions of target /ʃ/ (Figure 7-25 below). There is also evidence of an affricate, complete alveolar and double articulation pattern. The first production is similar to a MAG pattern type (section 2.5.4.1). Overall, the patterns for /ʃ/ are varied but DS08 achieves lateral bracing and grooving in 7 of the productions. Similar to /s/ productions above, when produced, the groove is asymmetrical making pattern classification more complex.

Figure 7-26 presents the alveolar closure scores for target /ʃ/ production, noting that DS08 shows a narrowing of groove at the start of the annotation and a widening at the end. Some of the productions have high scores suggesting narrowing to the point of complete closure at the front of the palate. This is shown in more detail in Figure 7-25 below. DS08's closure scores show different patterns to the TD group scores but this may be related to vowel production differences.

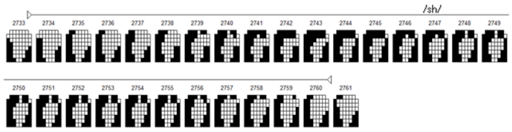
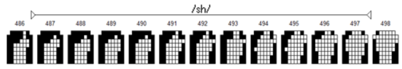
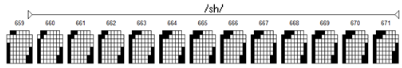
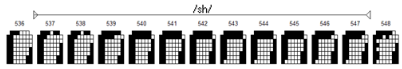
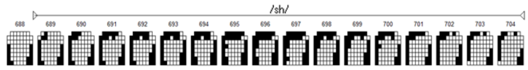
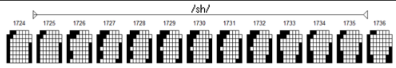
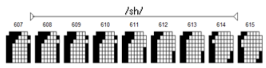
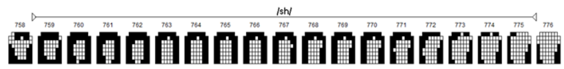
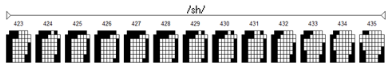
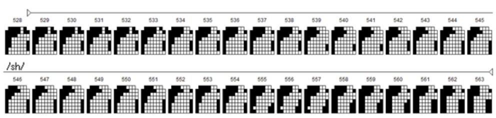
		Pattern Type	Transcription
1		double articulation	[ʃ]
2		affricate	[tʃ]
3		fronted groove	[ʃ]
4		complete alveolar closure	[d]
5		fronted groove	[z]
6		fronted groove	[ʃ]
7		fronted groove	[s]
8		complete alveolar closure	[tʃ]
9		fronted groove	[tʃ]
10		fronted groove	[ʃ]

Figure 7-25: Lingual palatal EPG contacts for all ten productions of target /ʃ/ from 'a sheep' for DS08. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-26 below.

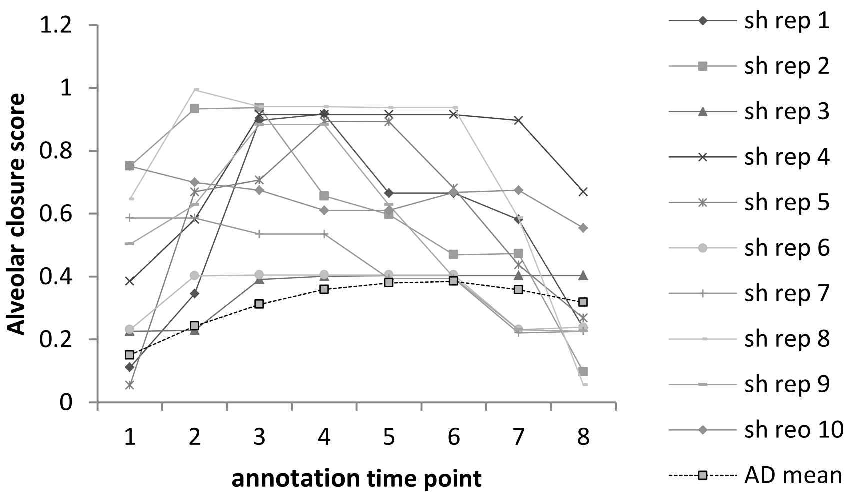


Figure 7-26: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /ʃ/ in 'a sheep': DS08. DS08 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /ʃ/ in 'a sheep'.

DS08's productions of /ʃ/ produce a similar average frame of maximum constriction when comparing with the /s/ productions, with less contact on the first row of the palate. Otherwise, it is not clear from the single average frame (see Figure 7-27) that DS08 creates a distinction between the two target sibilants.

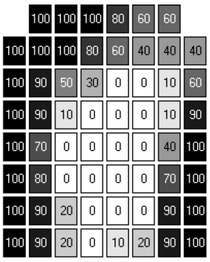


Figure 7-27: Single average frame of maximum contact from all repetitions of /ʃ/, DS08 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

The DEAP tokens of target /ʃ/ in Figure 7-28 also show the asymmetrical grooving pattern identified in the repetition data. The first production of 'sheep' looks very odd and is very probably due to problems with the child's contact with the handgrip during EPG recording. The other patterns are mostly WF productions of target /ʃ/ which are produced with a groove pattern, often fronted.

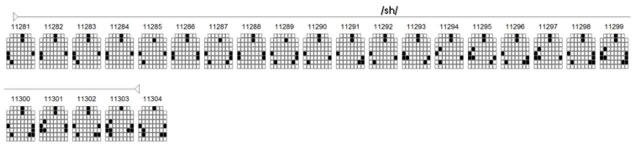
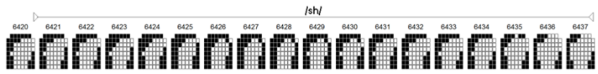
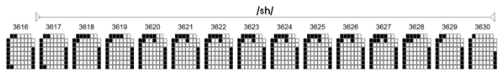
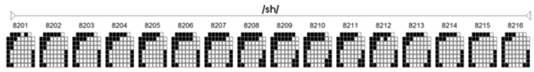
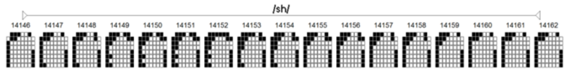
		Pattern Type	Transcription
Sheep		minimal contact	[ʃ]
Sheep		fronted groove	[z]
Fish		fronted groove	[ʃ]
Splash		typical pattern	[z]
Toothbrush		typical pattern	[ɬ]

Figure 7-28: Lingual palatal EPG contacts for all productions of target /ʃ/ from DEAP phonology assessment for DS08. Descriptive patterns types presented alongside agreed perceptual transcription.

7.4.2 Canonical Analysis

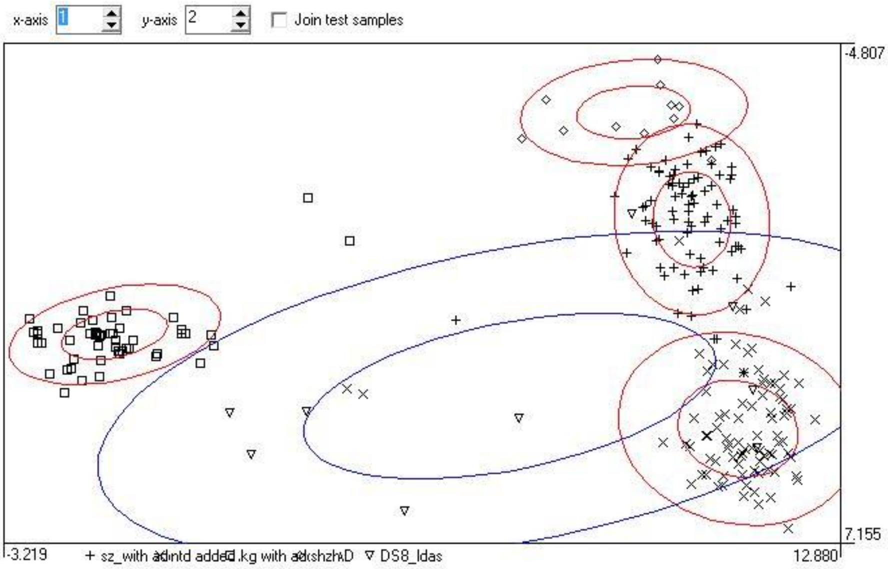


Figure 7-29: CA chart of target /s/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS08

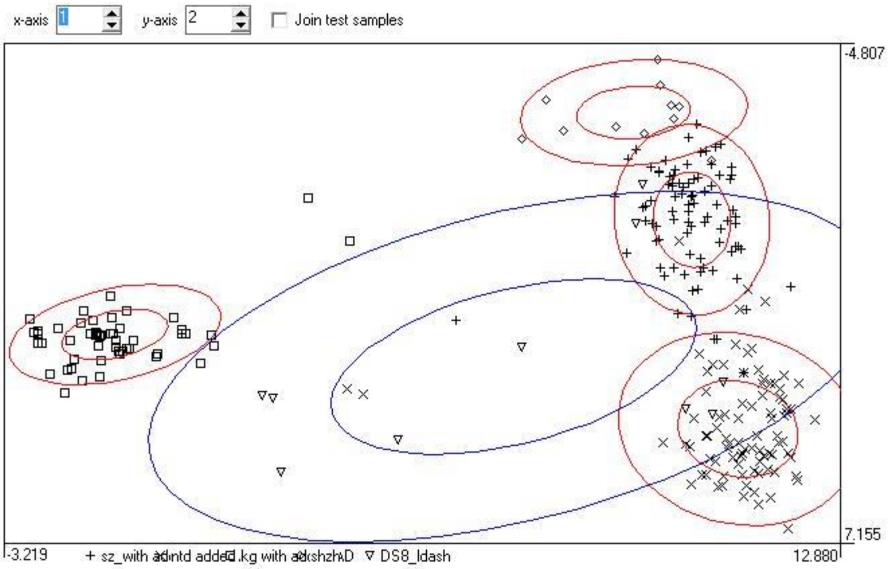


Figure 7-30: CA chart of target /ʃ/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS08

The CA analysis in Figure 7-29 shows that DS08's /s/ productions are retracted and sitting closer to the post-alveolar and velar regions rather than the alveolar regions. There is a wide spread here which suggests a wide variability across the articulation patterns, with some resembling /k/ or /ʃ/ more than /t/ or /s/. This may also reflect the variability in articulation achieved for target /s/. The productions of target /ʃ/ in Figure 7-30 below show a similar pattern (wide variability of articulation) but the productions of /ʃ/ occupy a slightly more anterior position, with a couple of tokens within the /s/ region. Again there is a wide spread suggesting articulation variability.

7.4.3 Motor ability and dentition

	DDK rate and accuracy									
	p		**t**		**k**		**tk**		**ptk**	
	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %
DS08	3.41	33.3	3.69	16.7	4.19	66.7	4.38	83.3	2.35	0
TD	*4.92*	*89.6*	*4.72*	*93.8*	*4.22*	*97.9*	*4.84*	*87.5*	*3.96*	*62.5*

Table 7-7: Mean DDK rate (syllables per second) and accuracy (% acceptable) for repetitions of /pə/, /tə/, /kə/, /təkə/ and /pətəkə/ by DS08, presented alongside the TD group mean scores

DS08 scored relatively high on the Robbins-Klee oral motor function test (90%). When compared with the TD means, his DDK rate scores in Table 7-18 below show a slightly slower rate for monosyllabic /p/ and /t/ production but similar rates for /k/ and /tk/ sequences. His trisyllabic rate is lower than the TD data. Accuracy levels are varied with DS08 showing higher scores for the /tk/ sequence compared to the monosyllabic tasks.

DS08 was identified as having a Class I malocclusion. This is where the teeth are severely crowded or there are problems with erupting teeth. There is little literature on the impact of a Class I malocclusion and speech production. For DS08, this crowding may explain why many of the articulations are asymmetrical. Warren et al. (1980) suggest that spatial asymmetries in /s/ production may be affected by the speaker's dentition and ability to bring lower and upper teeth together. It is hard to draw conclusions without any pictorial evidence but it may have an impact on the articulation patterns identified for this speaker.

7.4.4 DS08 Summary

DS08 presents with errors typical of a delayed development (/t/ and /s/ produced more successfully than /ʃ/), though supplemented with inconsistent atypical errors. He produces a variety of affricates, stops and fricatives for target /ʃ/ which is atypical, though the pattern analysis suggests that he fronts the articulations for most of the /ʃ/ repetitions. DS08 shows higher than TD variability scores for fricative production. This is evident in the OSVar, PSVar and COV of duration scores which, along with slower than normal (particularly in the tri-syllabic task) DDK rates, may suggest speech motor difficulties.

7.5 Speaker Four: DS16

DS16 is female and was 15;8 years old at the time of initial screening and speech data recording. Her hearing was aided to within normal limits. She presented with a low percentage of consonants correct from the DEAP assessment (40% compared to the average from this group, 62%) but her PTA scores show high scores for some target sounds. Her score of vowel productions from the DEAP was higher: 72% (compared to the average from this group, 83%). Verbal Age equivalent score was <4;1 and she scored 68% on the Robbins-Klee oral motor function assessment. Her results from the PhD study measures are presented in Table 7-8**.**

7.5.1 Segmental analysis

	target sound					
	t		s		ʃ	
DS16	DS16	**AV. TD**	DS16	**AV. TD**	DS16	**AV. TD**
quantitative measures						
%PTA	100	***100***	90	***93***	40	***91***
COG	4.77	***4.85***	4.17	***4.55***	4.08	***3.64***
Duration(ms)	170	***120***	250	***140***	260	***160***
COV of duration	0.36	***0.33***	0.61	***0.16***	0.91	***0.18***
OSvar	11.29	***7.17***	6.45	***7.39***	6.45	***9.39***
PSVar	11.29	***6.46***	6.09	***6.63***	5.65	***8.73***
WTM	0.51	***0.55***	0.27	***0.39***	0.28	***0.41***
descriptive measures						
%typical pattern	89	***91***	60	***79***	10	***59***
%retracted articulation	11	***2***	10	***6***		
%wide groove			20	***8***	40	***4***
%lack of groove			10	***2***		
%fronted groove					50	***14***

Table 7-8: Perceptual and EPG measures: DS16, PTA: Percentage Target Consonants Acceptable, COG: Centre of Gravity, Duration: length of annotation, COV duration: variability in length of annotation, OSVar: Overall spatial Variability, PSVar: Perceptually acceptable spatial variability, WTM: Whole Total Contact Measure. AV. TD: Average typically developing group scores

Perceptually DS16 produced target /t/ without error and presented only one error for target /s/, however, only 40% of /ʃ/ tokens were found to be perceptually acceptable. The COG scores for /s/ are slightly lower than the TD average. For /ʃ/ productions, the COG mean score is higher suggesting that productions are further forward than the TD average which may explain the low score for the perceptual analysis, which will be confirmed below. OSVar measures for fricative production are lower than the TD mean scores and this pattern remains once the errors are removed (PSVar). DS16 shows slightly higher than TD WTM scores for target /ʃ/ productions. The COV duration measures show that DS16 is much more variable in her production of fricatives compared to the TD average score.

7.5.1.1 /s/ EPG patterns

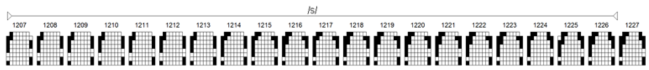
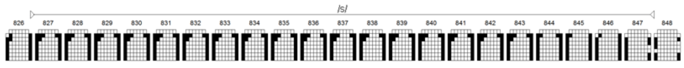
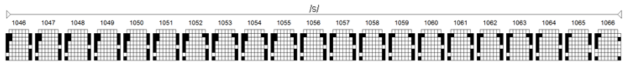
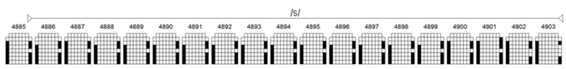
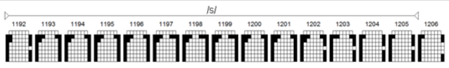
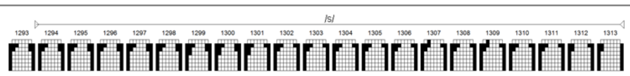
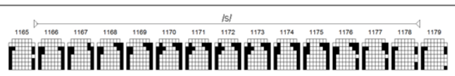
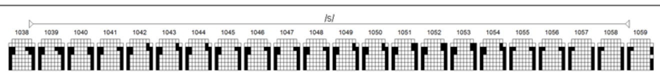
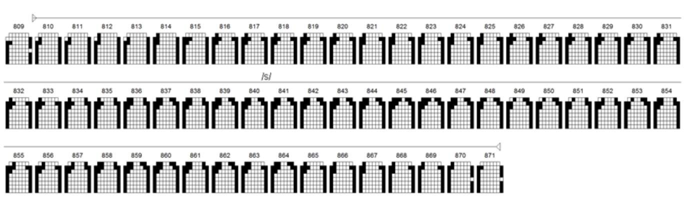
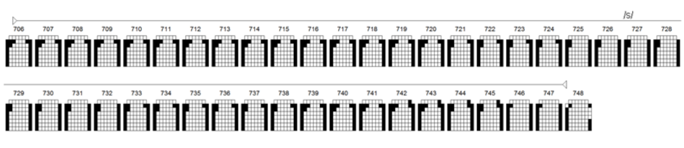
		Pattern Type	Transcription
1		typical pattern	[s]
2		typical pattern	[s]
3		wide groove	[s]
4		lack of groove	[s]
5		typical pattern	[s]
6		typical pattern	[s]
7		typical pattern	[s]
8		retracted pattern	[s]
9		typical pattern	[ˡs]
10		wide groove	[s]

Figure 7-31: Lingual palatal EPG contacts for all ten productions of target /s/ from ‘a sun’ for DS16. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-32 below.

The pattern analysis for /s/ productions shows a tendency to produce the typical alveolar fricative pattern but with some variability with groove width. Table 7-20 below presents the articulation patterns for /s/ productions.

DS16 displays a consistent range of articulations for target /s/. All patterns show a groove in the anterior part of the palate. At times the groove is wider than expected but situated at the acceptable place of articulation. The groove width varies from 2-6 electrodes, wider than TD and AD productions. There is one articulation where the narrowest part of the groove is more retracted than expected but yet still heard as [s]. DS16 provides a good example of the variation in acceptable articulation for perceptually acceptable /s/ production. This speaker uses a *lack of groove* pattern and *retracted pattern* for perceptually acceptable tokens.

Figure 7-32 below presents the alveolar closure scores for DS16's productions of target /s/. Most of the productions show an increase (reflecting a narrowing of the groove), and then a decrease as the groove widens again. The overall low scores show presence of wide grooving (compared to TD scores which can range from 0.5 to 0.8).

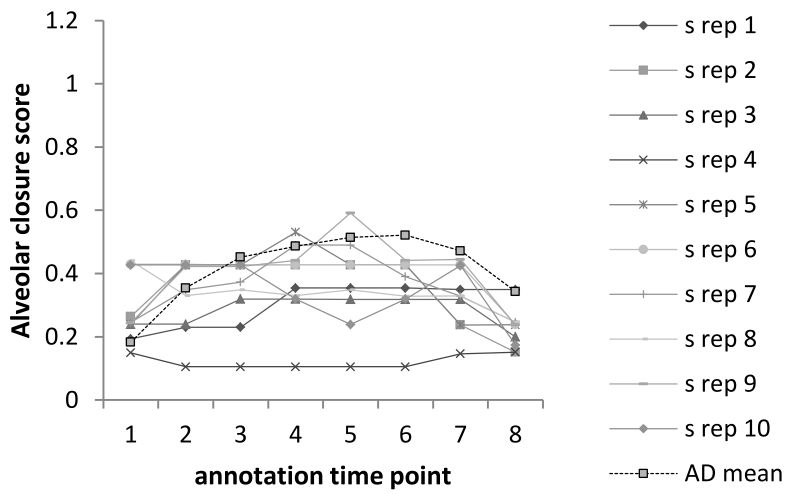


Figure 7-32: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /s/ in 'a sun': DS16. DS16 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /s/ in 'a sun'.

Although many of DS16's productions of /s/ are produced with a wide groove she does manage to create a grooved pattern, as shown below (Figure 7-33).

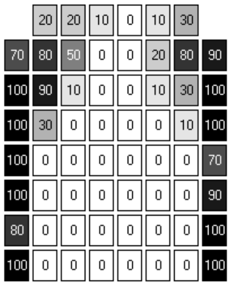


Figure 7-33: Single average frame of maximum contact from all repetitions of /s/, DS16 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

The composite pattern in Figure 7-33 above shows the consistency of grooving in DS16's productions of target /s/. This pattern is very similar to the standard pattern presented in Figure 6-1.

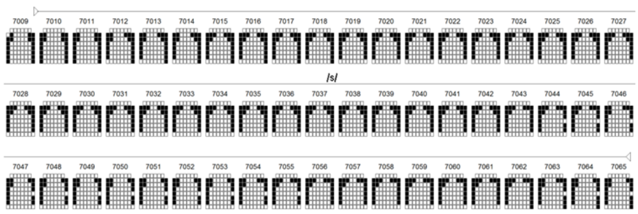
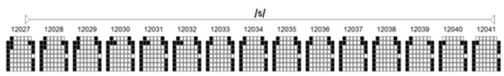
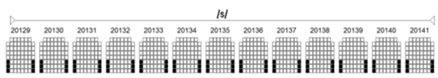
		Pattern Type	Transcription
sock		typical pattern	[s]
house		wide groove	[s]
scissors		minimal contact	[h]
lighthouse		complete alveolar closure	[t]

Figure 7-34: Lingual palatal EPG contacts for all productions of target /s/ from DEAP phonology assessment for DS16. Descriptive patterns types presented alongside agreed perceptual transcription.

In Figure 7-34 DS16 produces WI /s/ with an anterior groove pattern (though slightly wider than the standard pattern), the patterns presented for target /s/ appear to match the perceptual categorisation.

7.5.1.2 /ʃ/ EPG patterns

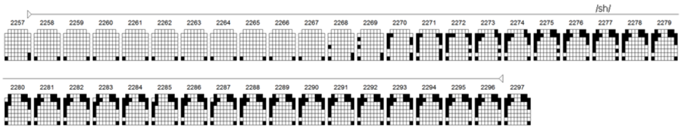
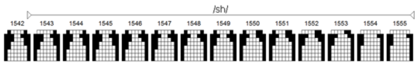
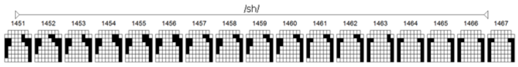
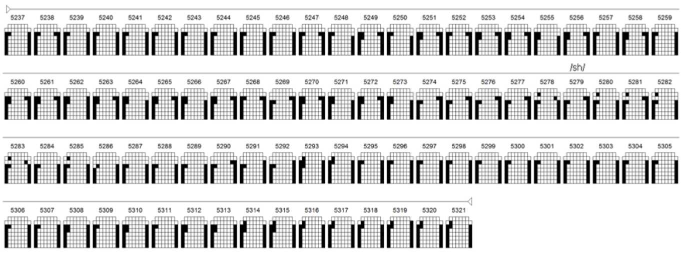
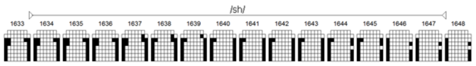
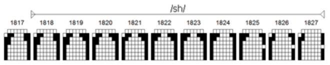
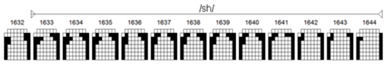
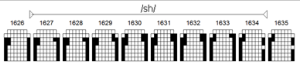
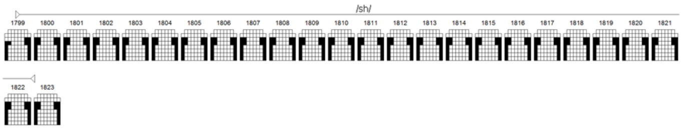
		Pattern Type	Transcription
1		fronted	[s]
2		fronted	[ʃ]
3		typical	[s]
4		wide groove	[s]
5		wide groove	[s]
6		fronted	[s]
7		fronted	[ʃ]
8		wide groove	[ʃ]
9		wide groove	[ʃ]
10		fronted	[s]

Figure 7-35: Lingual palatal EPG contacts for all ten productions of target /ʃ/ from 'a sheep' for DS16. Descriptive patterns types presented alongside agreed perceptual transcription. Numbers also relate to repetitions in Figure 7-36 below.

For /ʃ/ productions, 50% of the repetition productions were articulated with a fronted groove and 40% were produced with a wide groove. The EPG frames and transcription are shown in Figure 7-35 below. Although DS16 does not produce perceptually acceptable tokens of target /ʃ/ constantly she still produces an acceptable groove tongue configuration. The width varies across productions and there appears to be no relationship between width of groove and perception of fricative production. However, the acoustic output may be affected by the degree of lip protrusion created for the target sound. For example, we see a fronted groove pattern for repetitions 2, 7 and 8, perceived as an acceptable /ʃ/. As discussed in 2.4.6.2, this may be achieved by increasing the amount of lip protrusion to compensate for the anterior constriction, reflecting motor equivalence strategies. Furthermore, a typical post-alveolar fricative pattern perceived as a [s] may be related to the lack of a sub-lingual category, and lack of lip protrusion. Overall, the groove width for /ʃ/ productions varies between 2-5 electrodes.

The alveolar closure scores presented in Figure 7-36 reflect the variability of the groove width in these repetitions, which at times shows a similar pattern to the TD patterns.

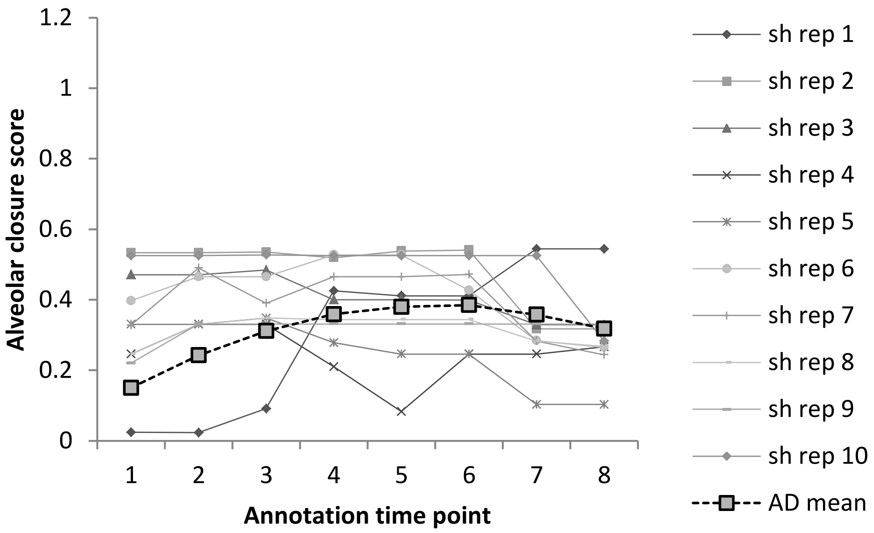


Figure 7-36: Lines represent Alveolar closure scores (numbers represent narrowing of lingual-palatal contact at the anterior portion of EPG palate: high number reflects more contact) across 8 time points for each annotation of 10 repetitions of /ʃ/ in 'a sheep': DS16. DS16 data presented alongside a mean alveolar closure score calculated from all AD repetitions of /ʃ/ in 'a sheep'.

Examination of the average frame of maximum constriction shows that DS16 consistently produces a narrow groove at the anterior part of the palate. The pattern is further forward than the standard adult pattern for /ʃ/ data.

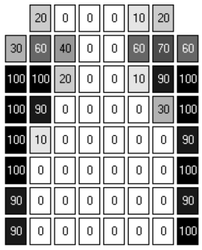


Figure 7-37: Single average frame of maximum contact from all repetitions of /ʃ/, DS16 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

Figure 7-38 shows that DS16 produces a grooved articulation for all productions of target /ʃ/ in the DEAP assessment. The groove width differs across the productions and the position is sometimes more anterior than expected. This is reflected in the transcription in one production of *sheep* but the other patterns considered to be fronted are transcribed as perceptually acceptable (which again may be a result of motor equivalence).

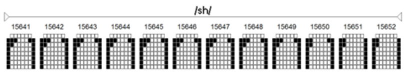
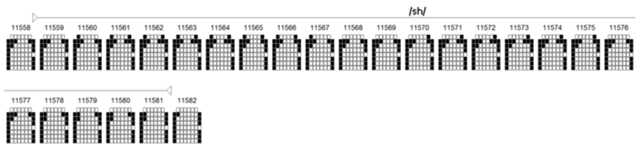
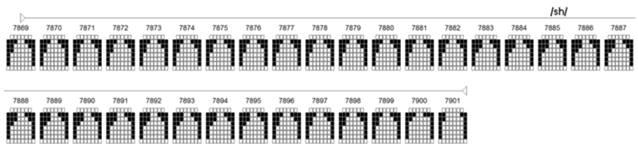
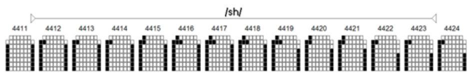
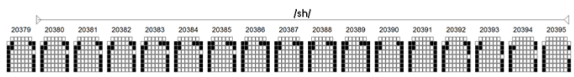
		Pattern Type	Transcription
sheep		fronted	[ʃ]
splash		fronted	[ʃ]
sheep		fronted	[s]
fish		wide groove	[s]
roothbrush		fronted	[ʃ]

Figure 7-38: Lingual palatal EPG contacts for all productions of target /ʃ/ from DEAP phonology assessment for DS16. Descriptive patterns types presented alongside agreed perceptual transcription.

7.5.2 Canonical Analysis

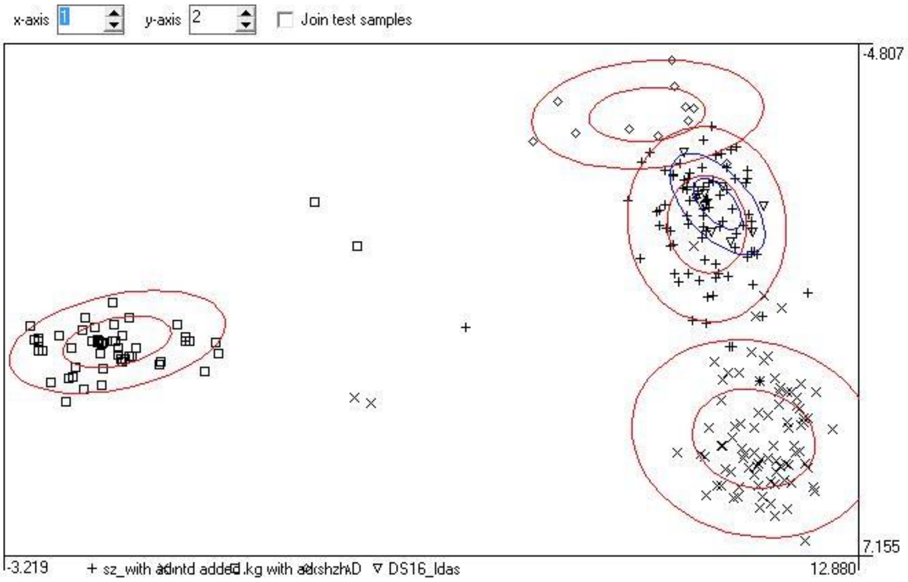


Figure 7-39: CA chart of target /s/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS16

The CA analysis chart in Figure 7-39 indicates that the productions for /s/ all sit within the trained area for /s/ AD productions. A similar pattern is shown for target /ʃ/ (Figure 7-40) which indicates that most of the productions were fronted articulations (similar to /s/ productions).

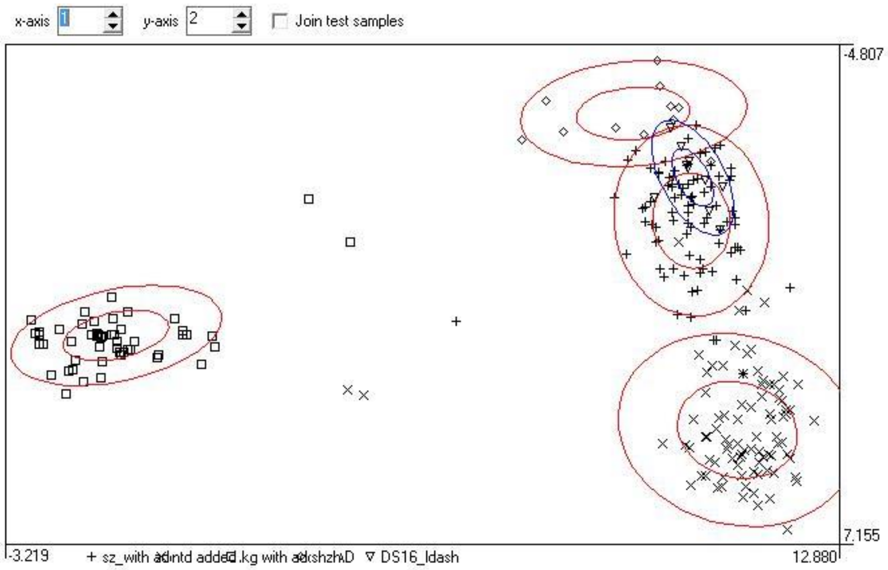


Figure 7-40: CA chart of target /ʃ/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns

7.5.3 Motor ability

DS16 scored 68% on the Robbins-Klee Oral motor function test and high levels of variability (for WI fricative production) as displayed by the COV of duration measures. The spatial measures above do not display variability of articulation scores that are any different to the TD speakers. However, the DDK measures in Table 7-9 suggest that DS16 has some motor difficulties with low rate scores for /k/, /tk/ and /ptk/ syllable sequencing. Her accuracy scores are low with no success for multisyllabic sequencing.

DDK rate and accuracy

	pə		tə		kə		təkə		pətəkə	
	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %
DS16	6.47	33.3	5.83	66.7	1.64	50	1.13	0	0.92	0
TD	*4.92*	*89.6*	*4.72*	*93.8*	*4.22*	*97.9*	*4.84*	*87.5*	*3.96*	*62.5*

Table 7-9: Mean DDK rate (syllables per second) and accuracy (% acceptable) for repetitions of /pə/, /tə/, /kə/, /təkə/ and /pətəkə/ by DS16, presented alongside the TD group mean scores

7.5.4 DS16 Summary

The results above indicate that DS16 presents with errors patterns similar to those identified in typically developing children. For example, the EPG evidence presents a grooved articulation for both target sibilants with a groove width that varies slightly in size and the articulations present with lateral bracing and narrowing in the majority of productions suggesting a typical articulation pattern. However, perceptually the errors produced were not typical substitutions and she presents with an inconsistent pattern of production.

This inconsistency is reflected in the high temporal variability (COV of duration in Table 7-8) identified for the target sibilants. As may be expected the related raw durations are also high. As noted (in 2.4.6.1) the maturation of temporal variability lags behind spatial variability in typical development. This suggests that DS16 presents with a similar profile (although delayed) to typical development. However, it has also been noted in studies of children with residual speech sound disorders that children with speech motor disorders may be highly variable in one phonetic feature but not necessarily in others (Preston & Koenig, 2011). The DDK results are harder to interpret as typical patterns considering the higher, and also lower, rate scores compared to the TD norms. While the bilabial and alveolar DDK tasks present with similar rates to the TD norms, DS16 shows greater difficulties with tasks involving the velar plosive. This study provides no data to further investigate the articulation success of velar targets for DS16, and accuracy levels are inconsistent across DDK tasks. Therefore, DS16 is shown to present with a mixed speech profile of typical and atypical articulation ability.

7.6 Speaker Five: DS23

DS23 is male and was 17;5 years old at the time of initial screening and speech data recording. He had a mild conductive hearing loss. He presented with a low percentage of consonants correct score from the DEAP assessment (19% compared to the average from this group, 62%). His score of vowel productions from the DEAP was higher than consonants but still very low: 36% (compared to the average from this group, 83%). Verbal Age equivalent score was <4;1 and he scored 55% on the Robbins-Klee oral motor function assessment. His results from the PhD study measures are presented in Table 7-10.

7.6.1 Segmental analysis

	target sound					
	t		s		ʃ	
DS23	DS23	**AV. TD**	DS23	**AV. TD**	DS23	**AV. TD**
quantitative measures						
%PTA	50	***100***	0	***93***	30	***91***
COG	3.44	***4.85***	2.03	***4.55***	2.15	***3.64***
Duration(ms)	90	***120***	60	***140***	90	***160***
COV of duration	0.24	***0.33***	N/A	***0.16***	0.13	***0.18***
OSvar	20.97	***7.17***	2.42	***7.39***	5.16	***9.39***
PSVar	6.05	***6.46***	-	***6.63***	5.91	***8.73***
WTM	0.36	***0.55***	0.13	***0.39***	0.18	***0.41***
descriptive measures						
%typical pattern	50	***91***				
%minimal contact	50	***0***	100	***0***	80	***0***
%velar constriction with lateral contact					20	***0***

Table 7-10: Perceptual and EPG measures: DS23, PTA: Percentage Target Consonants Acceptable, COG: Centre of Gravity, Duration: length of annotation, COV duration: variability in length of annotation, OSVar: Overall spatial Variability, PSVar: Perceptually acceptable spatial variability, WTM: Whole Total Contact Measure, AV.TD: Average scores from TD group

Perceptually, DS23 scores far below typical average for all 3 target sounds. He has no successful production of target /s/ but 3 productions of target /ʃ/ are considered perceptually acceptable, and 50% of /t/ productions were acceptable.

The COG scores for DS23 are much lower than the TD averages suggesting that most of these productions are produced at the back of the palate, particularly for the fricatives which show similar COG scores to each other. The OSVar score for target /t/ is much higher than the TD mean but much lower for target /s/. This may be related to the lack of lingual contact (less variability can occur if there are less EPG contacts to measure). The PSVar scores for /t/ are similar for DS23 and the TD mean. Target /s/ cannot be measured as there are no perceptually acceptable tokens but the TD mean and DS23's PSVar for /ʃ/ are close (with DS23 showing a lower score). The WTM suggests that there is less lingual-palatal contact for these target sounds that expected for the typical speakers. The pattern analysis confirms the EPG quantitative measures as the favoured articulation type for this speaker is *minimal contact* for both sibilants (and also 50% of the target /t/ productions).

7.6.1.1 /s/ EPG patterns

Table 7-26 below confirms the EPG analyses results discussed above. The productions of target /s/ were either heard as a voiced palatal or voiceless velar fricative.

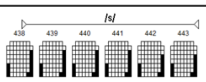
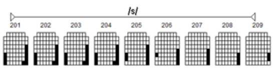
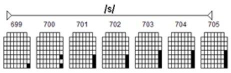
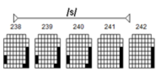
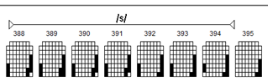
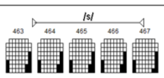
		Pattern Type	Transcription
1		minimal contact	[x]
2		minimal contact	[x]
3			
4			
5		minimal contact	[x]
6		minimal contact	[j̥]
7			
8		minimal contact	[j̥]
9		minimal contact	[j̥]
10			

Figure 7-41: Lingual palatal EPG contacts for all ten productions of target /s/ from 'a sun' for DS23. Descriptive patterns types presented alongside agreed perceptual transcription.

There were few tokens produced for target /s/ in the repetition data as can be seen in Figure 7-41, in the other productions the /s/ was omitted**.** For all attempts at /s/ production there is little lingual-palatal contact, with the contact situated at the posterior part of the palate. Due to the lack of anterior contact, no alveolar closure measures could be performed on DS23's repetition data. The perceptual analysis identified target /s/ productions to be posterior fricatives. The composite frame in Figure 7-42 below confirms the lack of variation and lingual-palatal contact in articulation of /s/.

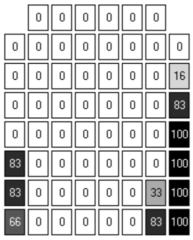


Figure 7-42: Single average frame of maximum contact from all repetitions of /s/, DS23 (repetition data). Shading represents amount of contact (darker = more contact). Numbers represent amount of lingual contact with electrode across all productions (100 = constant, 0 = no contact).

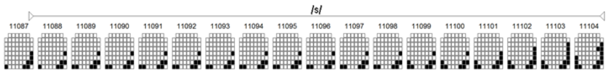
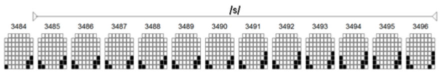
		Pattern Type	Transcription
scissors		velar constriction with lateral contact	[g]
sock		velar constriction with lateral contact	[g]

Figure 7-43: Lingual palatal EPG contacts for all productions of target /s/ from DEAP phonology assessment for DS16. Descriptive patterns types presented alongside agreed perceptual transcription.

In Figure 7-43, DS23 displays a similar pattern of production for /s/ in the DEAP assessment, with the pattern used identified as *velar constriction with lateral contact.*

7.6.1.2 /ʃ/ pattern analysis

The EPG patterns for target /ʃ/ in Figure 7-44 show posterior contact with some lateral contact. Overall, the contact shows lateral contact with some narrowing at the velar position, and no evidence of alveolar contact. This may suggest that DS23 does not have independent control over the tongue tip and tongue body. The pattern analysis for target /ʃ/ shows a consistent pattern in line with the articulations for target /s/. The patterns here appear to show more lingual-palatal contact than for target /s/ productions. The WTM measure is slightly higher for target /ʃ/ productions than target /s/ productions. It may be that DS23's patterns for /ʃ/ show more lingual palatal contact as this consonant is produced with a high vowel which has a similar pattern of contact to the patterns in Table 7-18. Sanders (2007) noted more lingual-palatal contact for consonants in high vowel contexts and Lavoie (2001) notes that high vowels (such as /i/) have a coarticulatory influence on the amount of lingual-palatal contact on adjacent consonants more so than low vowels.

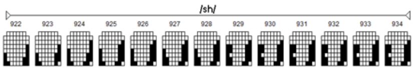
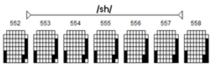
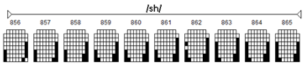
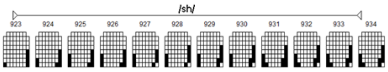
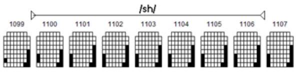
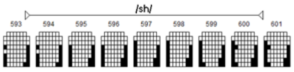
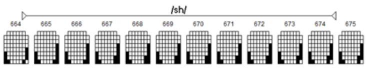
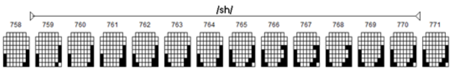
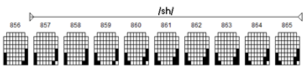
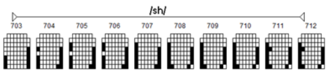
		Pattern Type	Transcription
1		velar constriction with lateral contact	[ʃ]
2		velar constriction with lateral contact	[x]
3		velar constriction with lateral contact	[ç]
4		Velar constriction with lateral contact	[ʒ]
5		minimal contact	[h]
6		velar constriction with lateral contact	[ç]
7		velar constriction with lateral contact	[ʃ]
8		velar constriction with lateral contact	[ʃ]
9		minimal contact	[x]
10		velar constriction with lateral contact	[ç]

Figure 7-44: Lingual palatal EPG contacts for all ten productions of target /ʃ/ from 'a sheep' for DS23. Descriptive patterns types presented alongside agreed perceptual transcription.

However, in the case of DS23 the vowel presence may be the only articulation he is attempting (this may also explain the palatal fricatives that are produced for target /ʃ/, as they share the same place of articulation as the vowel /i/). The retracted pattern displayed in the productions of /s/ and /ʃ/ in the repetition data is also found in the productions from the DEAP assessment. In Figure 7-45 DS23 produces target /ʃ/ in a retracted place of articulation, with some evidence of lateral contact. Target /ʃ/ was not always produced in the context of a high front vowel, so the above suggestion that the lateral contact is an influence of the vowel context may not be acceptable.

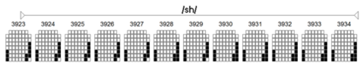
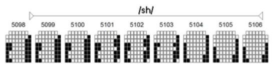
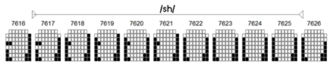
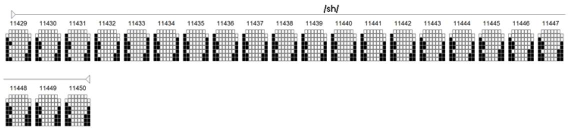
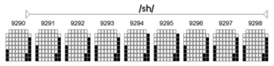
		Pattern Type	Transcription
sheep		minimal contact	[ç]
splash		typical pattern	[ç]
sheep		lack of groove	[ç]
fish		lack of groove	[ç]
toothbrush		lack of groove	[ʒ]

Figure 7-45: Lingual palatal EPG contacts for all productions of target /ʃ/ from DEAP phonology assessment for DS16. Descriptive patterns types presented alongside agreed perceptual transcription.

7.6.2 Canonical Analysis

The canonical analysis of /s/ (Figure 7-46 below) shows that DS23 is producing a posterior articulation for all attempts at target /s/, which presents with little similarities to either /s/ or /ʃ/.

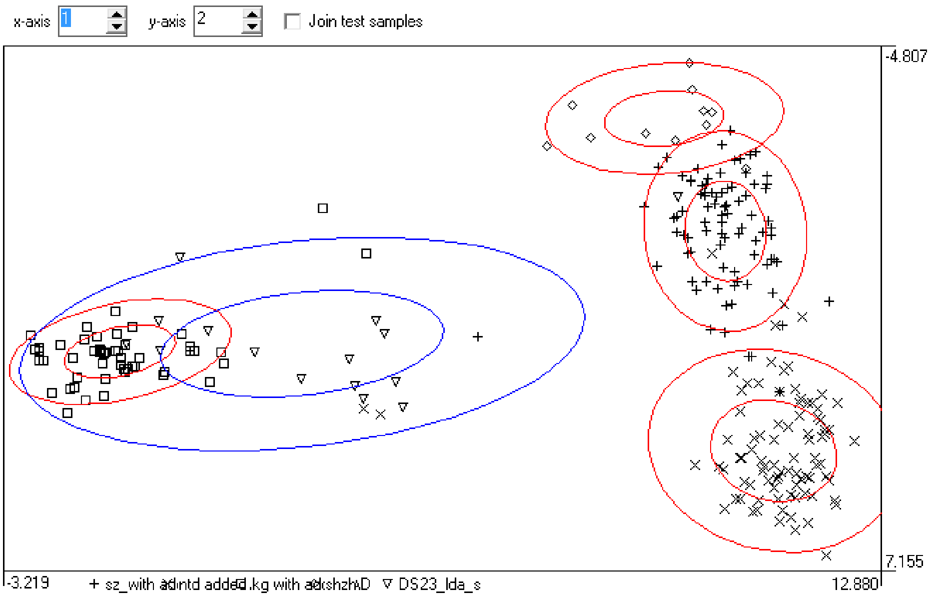


Figure 7-46: CA chart of target /s/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS23

As expected from EPG patterns presented above, the canonical analysis of target /ʃ/ shows similar posterior articulations but some of these productions are produced in a more anterior space, leaning slightly towards /t/ and /s/, rather than /ʃ/.

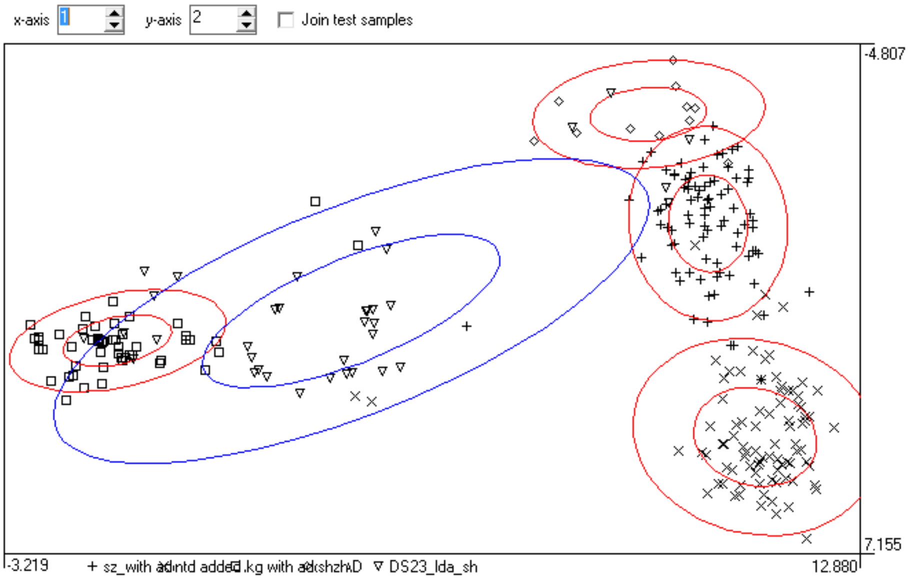


Figure 7-47: CA chart of target /ʃ/ (∇) compared with AD /t/ (◊), /s/ (+), /ʃ/ (X) and /k/ (☐) patterns: DS23

7.6.3 Motor ability

DS23 scored 55% on the Robbins-Klee Oral Motor function test and shows low spatial variability scores for the production of target fricatives. His DDK scores in Table 7-11 show similar (or slightly higher) rates for monosyllabic tasks to the TD group mean scores but lower scores than the TD mean for the multisyllabic tasks. As mentioned above, low rates for trisyllabic productions in DDK tasks have been suggested to be a sign of CAS. Even with high DDK rate scores, DS23 presents with very low levels of accuracy, indicating no link between speech production ability and rate.

	DDK rate and accuracy									
	p		**t**		**K**		**tk**		**ptk**	
	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %	rate sy/sec	accuracy %
DS23	6.68	16.7	5.91	0	5.38	16.7	2.63	0	2.13	0
TD	*4.92*	*89.6*	*4.72*	*93.8*	*4.22*	*97.9*	*4.84*	*87.5*	*3.96*	*62.5*

Table 7-11: Mean DDK rate (syllables per second) and accuracy (% acceptable) for repetitions of /pə/, /tə/, /kə/, /təkə/ and /pətəkə/ by DS23, presented alongside the TD group mean scores

7.6.4 DS23 Summary

DS23 has the lowest PTA scores of the DS group and his overall pattern of articulation is a retracted minimal amount of contact. He presents with typical levels of spatial variability but DDK scores show lower than typically average scores for multisyllabic productions. DS23 presents with an atypical profile. He presents with little precision in articulation but his sequencing scores are similar to the TD mean scores. Overall evidence from sibilant production suggests that DS23 has difficulty with tongue tip/blade articulations. However, analysis of other target productions suggest otherwise. DS23 manages to create a typical horseshoe pattern of articulation for 4 productions of target /t/, suggesting a particular difficulty with sibilant constriction.

DS23 presents with a mild conductive hearing loss. As mentioned for DS24, this data cannot support the claim that a causal link is present between hearing loss and sibilant production. However, both DS24 and DS23 present with atypical articulation patterns compared to the other participants included in this chapter. These results may support further investigation of the role of auditory feedback in the successful production of sibilants in children with DS.

7.7 Chapter summary

The five speakers presented here were selected on the basis that they spanned the range of the lowest to the highest phonology scores on a standardised speech assessment. These perceptual scores do not map straightforwardly onto the EPG data which can be expected as EPG only provides information regarding the lingual-palatal contact of speech sound production. Also, the transcription presented is very broad and therefore lacks detail regarding non-lingual-palatal phonetic information. This may be particularly relevant for DS24 who presents with high levels of lingual-palatal contact, but acceptable productions. Narrow phonetic transcription could have provided further insights into the articulation of these sounds (Howard & Heselwood, 2011). On reflection, a further weakness of this data is the omission of acoustic information alongside the EPG and perceptual representations (as discussed in more detail in Chapter 8).

It is clear from the data above that speakers presented in Chapter 7 are all different in their articulatory abilities.

- DS10 presented with perceptually acceptable productions for /s/ and 1 instance of *fronting* for /ʃ/, suggesting a typical profile (with also no evidence of delay).
    - Patterns of production for both /s/ and /ʃ/ support the perceptual findings, both fricatives are produced with anterior narrow groove with varying widths
    - DDK rate measures present similar to TD (though slightly faster for monosyllabic repetitions). Accuracy is similar to TD, except for tasks involving bilabials (i.e. /p/ & /ptk/).
- DS16 showed a more delayed profile with perceptual errors mostly in /ʃ/ production (with one lateral+central error for /s/ production).
    - EPG patterns of articulation show grooved articulations for both target fricatives, with varying groove widths
    - DDK tasks note lower than TD rates for multisyllabic tasks, and higher for monosyllabic tasks. Accuracy scores are lower than TD.
- DS08 has some perceptual errors in sibilant production. Errors are slightly more complex than DS16 with lateral +central for /s/ but affricate, fronting and stopping for /ʃ/.
    - Both /s/ and /ʃ/ patterns show asymmetry but also presence of atypical articulation patterns, this variation is reflected across articulations with varying alveolar closure scores
    - DDK scores are mostly similar to TD mean but shows low rate for trisyllabic task. Accuracy scores so no real pattern, except no successful productions identified for /ptk/.
- DS24 and DS23 present the most atypical errors out of the 5 studies.
- DS24 produces perceptual errors of stopping, voicing, affrication, lateral+central for target /s/, and debuccalisation and lateralisation for target /ʃ/.
    - EPG patterns show anterior horseshoe-like productions with varying amount of lingual-palatal contact, particularly for /s/. /ʃ/ presents as more atypical with full palatal contact almost achieved.

    - DDK tasks note typical rates for monosyllabic tasks but lower rates for multisyllabic tasks. Accuracy is low for all DDK tasks.
- The perceptual errors produced by DS23 are more diverse with error substitutions including palatals and velars for /s/, and velars, palatals, voicing and debuccalisation for /ʃ/.
    - EPG patterns are very consistent showing posterior articulations with more anterior lateral contact for /ʃ/ productions than /s/.
    - DDK rates are higher than TD averages for the monosyllabic tasks but much lower rates for multisyllabic tasks. Accuracy scores are very low (reflecting his overall poor speech ability)

The speakers discussed in this chapter are all different in their articulatory abilities. The EPG measures vary across speakers, with some presenting more variability in spatial and temporal dimensions than the TD group but others not. The pattern analysis provides more information about the atypical patterns used by some of the speakers, and typical patterns used by others.

Perceptually and articulatorily, DS10 shows an almost typical profile while DS08 and DS16 show an inconsistent profile. DS24 is more atypical (with more errors in /t/ than /s/) than the other speakers, particularly in the findings of the pattern analysis. DS23 also presents with an atypical profile with little lingual-palatal contact which is mostly posterior. All of the speakers have difficulties with the trisyllabic DDK task except DS10. However she presents with problems with accuracy in this task. Overall, these results show a wide range of abilities in the group of children with DS.

Information from these case studies can provide more insight into articulation difficulties in sibilant production in DS. For instance, the articulation of the narrow central groove is a difficult constriction for these speakers to maintain. Those who produce a groove as narrow as 1-2 electrodes are not consistently doing so. A wider groove is used more often in these speakers, even in those productions which are perceptually acceptable. The measures presented here provided additional information regarding speech motor abilities (DDK), pattern/perceptual relationships and a descriptive look at sibilant dynamics. All these provide more evidence to support hypotheses presented in 2.7. There are doubts about the additional value in the Canonical analysis presented in this chapter but this will be further discussed in 8.7.5.4.

8 Discussion of results and conclusions

8.1 Introduction

While much is known of the speech and language difficulties presented in speakers with Down's syndrome (DS), evidence is lacking of fine articulatory ability. This information can provide evidence of motor deficiencies, and has the potential to uncover the underlying cause of articulation difficulties in this group. Subsequently, increased understanding of the speech errors and their causes has the potential to inform articulation intervention in children with DS.

The main aim of this study was to provide a detailed analysis of sibilant fricative articulation in young people with DS with a view to learning more about speech motor control (using the articulatory analysis technique, Electropalatography (EPG)). It was hypothesised that EPG would provide information relating to aspects of speech motor control (identified via the nature of articulatory problems these speakers have in comparison to a typically developing control group) and provide further information regarding the nature of the speech difficulties previously unidentified in DS. This information was derived from a series of analysis techniques: perceptual analysis, EPG quantitative measures (spatial and temporal variability, palate closure scores, tongue placement and amount of contact measures), EPG descriptive measures (visual examinations and categorisation) and sequencing measures (DDK tasks). This chapter will present three sections that relate to the research questions posed in 2.7. Section 8.2 will discuss the results that relate to the question: Do children with DS show more atypical articulation patterns in errors of sibilant production in comparison to TD and typical AD? Section 8.3 discusses the results in relation to the second research question posed: is there evidence of speech motor difficulties in children with DS as measured by spatial and temporal variability? Section 8.4 will provide a discussion of the results in regard to the final research question: Do children with DS present with atypical EPG measures and patterns for perceptually acceptable productions of sibilants? A discussion of other findings from the study that were not part of the original investigation is presented in section 8.5 and section 8.6 considers the impact of other factors, not measured in this study, on speech in DS. The chapter concludes with a critical review of the investigation in section 8.7, directions for further research following in 8.8, and a summary and conclusion in 8.9.

8.2 Sibilant production in young people with DS compared to TD and AD speakers

8.2.1 Perceptual measures

It is well-established in the literature that children with DS present with more errors in consonant production than typically developing (TD) children (Dodd & Thompson, 2001; Roberts et al., 2005; Rosin et al., 1988; Rupela et al., 2010; van Borsel, 1996; van Bysterveldt, Gillion & Foster-Cohen, 2010). The children with DS in this study show significantly lower PTA scores than cognitively-aged matched TD children and adults (AD) for target sibilant production (/s/ 61%, /ʃ/ 44%, compared to TD: /s/ 94%, /ʃ/ 86%). Sibilant errors in children with DS are commonly reported. Roberts et al. (2005) note a mean percentage consonants correct (PCC) score of 38% for later-developing consonants (which includes both /s/ and /ʃ/, Shriberg & Kwiatkowski, 1982) in a larger group of children with DS (32 speakers, aged 4-13 years). Van Bysterveldt (2009) however, reports higher PCC-R scores for the same set of later developing consonants (mean 52.5, SD: 18.2) in a much larger group of children with DS but over a similar age range (77 children with DS, aged 5-14 years). Both van Bysterveldt (2009) and Roberts et al. (2005) present decreasing scores for early, middle and late consonants, but neither present scores for individual target sounds. These studies report on a larger set of consonants than reported here. However, Sommers et al. (1988) and van Borsel (1996) present scores for /s/ and /ʃ/ in adolescents with DS which align closely to those presented here.

While the PTA scores represent the perceptual differences between the group with DS, and the TD group, they provide no detail regarding the error types produced in each group. It was hypothesised (H3) that the perceptual analysis would reveal more atypical errors in the production of voiceless sibilants in the speakers with DS, compared to the TD and AD groups. The phonetic error (PE) analysis found that the DS group showed overall more errors in all articulatory features but most were identified in manner, then place, and then voicing for /s/ production, which was different to the pattern of errors identified in the TD group, who had more errors with place than manner. In contrast, the PE pattern for /ʃ/ was similar in both groups with place, manner then voicing being problematic. Similar measures of speech production in the literature present mixed findings. Van Borsel (1996) presented a similar measure of the errors made by 20 older children and adults with DS, compared with 20 cognitively age-matched TD children and found similar patterns in both groups with regard to areas of difficulty, with most errors in voicing, then place and then manner of articulation. However, the ages (15-28 years) and native language (Dutch) of these speakers are different to those presented in this current study and the van Borsel study presented results for all target consonants. On the other hand, Smith & Stoel-Gammon (1983) did assess errors more specifically, and similarly to van Borsel found that their 5 children with DS (aged 3-6yrs) produced more voicing errors in their incorrect plosive productions than any other error. These children are much younger than those in this study, but also those in van Borsel (1996), which suggests that errors identified in this study are not related to age. Conversely, Bunton et al. (2007) identified more problems with placement (in particular for fricative production) than manner or voicing in a phonetic error analysis of 5 adult male speakers with DS, which also do not support findings in this study. Hence, the literature is divided in the reporting of which feature is most affected in production errors though studies report on different ages and languages. All previous mentioned studies vary in their participant groups and methodologies. Bunton et al. (2007) and van Borsel (1996) report on older speakers, whereas Smith and Stoel-Gammon (1983) report on younger children. Findings do not differ in relation to age, so other explanations are required. For example, the high levels of between-speaker variability may have affected results (particularly in the smaller studies, Bunton et al., 2007; Smith & Stoel-Gammon, 1983). The findings in this study may also be different to the other child-based studies due to the specificity of the data, namely only three sounds analysed in one word position (compared to all English phonemes in the studies by Bunton et al. and Van Borsel). The errors in this study for /s/ production are more in line with expected patterns of typical speech development where *stopping* is the most common substitution error for target /s/ (thus an error of manner rather than voicing or placement). The TD speakers do not show this typical pattern in the small amount of /s/ errors produced, but this may be as the TD group errors are confined to only two speakers, who show some individual differences that do not reflect the rest of the group. Additionally, the increased difficulty, for the speakers with DS, with manner may relate to the specific muscular control required for the sibilants. The narrow groove constriction is possibly the most complex part of /s/ production for these speakers, thus articulations are commonly produced with a lack of central friction. The DS and TD groups show similar patterns in the errors produced for /ʃ/, but more speakers in the TD group have errors in this sound, which may mask any individual differences.

To further investigate H3, an error pattern analysis approach was taken to assess the nature of the perceptual errors produced for sibilant production in TD children and those with DS. Previous studies of phonological patterns in children with DS have identified presence of typical error patterns but also some evidence of atypical patterns (as found in Cleland et al., 2010; Roberts et al., 2005; Sokol & Fey., 2013). The findings in this study identified higher presence of atypical errors than previously reported, with 17 of the 25 participants presenting with atypical errors. This group used backing, palatal and lateral substitutions and many other types (see section 5.2.3) not commonly discussed in reference to process analysis of typical speech production or noted in this small TD group. Some of these errors have been previously identified in the speech production of children with DS, for example, backing of /s/ (Dodd, 1976; So & Dodd, 1994), and lateralisation (Roberts et al., 2005; Van Borsel, 1996). Aside from Cleland et al. (2010) who report on a smaller sample of the same dataset reported in this thesis, the other perceptual errors have not been reported in the literature to date. Sokol and Fey (2013) briefly discuss velar and palatal substitutions in their data but these were removed from their analysis. In summary, the findings in this study provide evidence of more atypical errors in sibilant production in children with DS compared to a cognitively age-matched TD group of children. In addition to the atypical errors, typical error patterns (*stopping*, *voicing* and *fronting*) were also identified for sibilant production in the children with DS. These findings have been previously identified in children with DS, e.g. *stopping* of /s/ (Bleile & Schwarz, 1984; Bodine, 1974; Dodd, 1976; Mackay and Hodson, 1982; Roberts et al., 2005; Rupela & Manjula, 2007; Smith & Stoel-Gammon, 1983; Shriberg & Widder, 1990; van Bysterveldt et al. 2010) and *fronting* of /ʃ/ (Dodd, 1976; Rupela et al., 2010; Shriberg & Widder, 1990). Overall, the error pattern analysis results for the DS group found that there were more atypical than typical error patterns used for sibilant errors.

Correlations were run to further investigate differences between the perceptual measures and chronological age to address whether children with DS present with any age-related differences (as expected in TD children). There is little evidence for a relationship between chronological age and speech production in older children with DS and studies into language have noted that development plateaus in young adulthood (Abbeduto & Chapman, 2005). Rondal (2009) has noted that adult speakers with DS show similar patterns to those of older children with DS (citing Rondal & Lambert, 1983; Van Borsel, 1988) which may suggest that speech development plateaus around the same time as language development. Smith and Stoel-Gammon (1983) provided longitudinal data from children 3-6 years and found that processes disappeared as the children aged but there is little information available for older children with DS. Sommers et al. (1988ab) found presence of phonological processes in all participants in their study of young adults (15-22 years) with DS, suggesting that processes are constant in the speech of children with DS to a much later age than typically developing children. The findings of this PhD study suggest that there is no relationship between chronological age and production of sibilant fricatives in children with DS.

8.2.2 Quantitative EPG measures

It was hypothesised (H4) that the centre of gravity (COG) scores for the target sibilants would reveal differences between children with DS, and the TD and AD group, with the DS group presenting with less COG distinction between the sounds, supporting findings from Callahan-Mandaluk et al. (2006). The results supported this hypothesis as the group with DS showed less distinction between COG scores than the TD and AD group (this has also been noted for speakers with hearing impairment, Perkell et al. 2004). Although all three groups showed similar patterns of lingual palatal placement for sibilant production, there was a trend of a more posterior articulation for /s/ in the DS group compared to the control groups and although this was not significant, it may indicate increased tongue-body articulations (Gibbon, 1999). Additionally, individual measurements reflected the between-speaker variability in this group, as not all individuals presented with the typical relationship between /s/ and /ʃ/ COG measures. Three of the speakers with DS, and one TD speaker, show the same COG measure for both fricative sounds suggesting no placement distinction between the two, also noted in Gibbon and Lee (2011). Only one speaker, DS14, presents with a relationship opposite to the TD and AD speakers (COG scores suggest that /ʃ/ is produced further forward than /s/). Returning to the data, these scores seem accurate as many target /s/ productions show posterior errors (perceived as palatal and velar substitutions). However, EPG patterns for errors of the post-alveolar sibilant are much more anterior. Perceptually, these errors were often bilabial substitutions. The anterior contact produced for these errors may suggest a lingual-labial double articulation, as identified for speakers with cleft palate (Gibbon & Crampin, 2001).

Overall the individual DS COG results present similar findings to the TD group. This was unexpected as the most common perceptual error for /ʃ/ in the group with DS was fronting. However, this mismatch of perceptual and articulatory information may be explained by lack of lip protrusion, or the absence of a sub-lingual cavity during the production of target /ʃ/, suggesting that the lingual-palatal contact may be similar but the acoustic results are different. For those speakers who show a distinction between the mean COG scores, most of the errors for target /s/ were produced in the alveolar region and the errors for target /ʃ/ were often post alveolar or produced in a more retracted position in the oral cavity. There was no evidence for covert contrast in these speakers, as the errors for each target sound were generally different. This suggests that children with DS are attempting different phonological targets, but may experience difficulties with the motor programming and execution of these targets (as suggested by Dodd, 1976). However this may also suggest that the underlying phonological representations are incorrect, possibly as a result of impaired auditory feedback (Hulme & Mackenzie (1992), as cited in Rodger, 2009).

Further evidence of atypical speech patterns was provided from correlations between EPG quantitative measures and age. In their typical EPG study, Cheng et al. (2007) identified a trend for more anterior productions of alveolar target sounds in older children. This relationship was investigated for both the DS and TD groups via the COG measurement. No significant age relationships were identified for any COG measures within the TD group. However, a weak significant negative relationship was identified for /ʃ/ COG scores overall and age for the children with DS. This relationship may be explained by the presence of minimal posterior articulation errors for two of the older children. The correlation result is not strong enough to support an age relationship.

Although nearly all speakers show a distinction between /s/ and /ʃ/ in relation to COG scores, the size of that distinction differed between the groups. Previous noted differences between TD and AD /s/ and /ʃ/ distinctions (Gibbon & Lee, 2011; Nissen & Fox, 2005; Nittrouer et al., 1989) were also supported in this study. Moreover, the TD participants who presented with perceptual errors for the target sibilants still showed clear COG distinctions, suggesting evidence for covert contrasts (supporting findings from Li et al. 2009).

Based on previous work by Hamilton (1993), it was hypothesised (H5) that speakers with DS would show significantly more lingual-palatal contact during productions of target sounds than the TD and AD groups. Additionally, based on Cheng et al. (2007) who found that children use more lingual-palatal contact than adults in their productions of /t/ and /l/ (also in /s/ for male speakers), it may also be expected that a difference would be noted between the TD and AD group. The WTM measures of sibilant production in speakers with DS did not support this hypothesis (but there were significantly higher levels of lingual palatal contact for target /t/ in the group with DS). The investigation of individuals with DS found some speakers presenting with very high scores for lingual-palatal contact (WTM scores) and those with very low scores. Both extremes (high and low WTM scores) may reflect difficulties controlling the tongue tip/blade independently from the tongue body. Lack of lingual control has been related to high levels of lingual palatal contact (e.g. Hardcastle et al., 1989). Furthermore, Hardcastle et al. (1985) suggest that articulatory undershoot occurs due to insufficient muscular tension in the articulatory muscles, which may be expected from a group of speakers with hypotonia. These overall findings contrast with Hamilton's study. However, Hamilton's small study was limited to data from three older speakers with DS, and while the patterns identified in her study were also noted in this group of 25 speakers, patterns of decreased lingual palatal contact (particularly for target /ʃ/) were also identified here that may not be found in a small group of speakers.

In typical EPG speech research, increased lingual-palatal contact has been related to chronological age, with higher levels of lingual palatal contact noted in younger children (Fletcher, 1989). Similarly, Cheng et al. (2007) identified a clear trend of lingual palatal reduction in the production of /t/, /l/ and /s/ in their large group of typical speakers providing evidence of the maturation of speech motor control abilities and reflecting changes in palatal shape and size. Spearman's Rho correlations were run to assess whether children with DS presented with this age-related difference. Surprisingly, the TD group showed no significant relationship for age and lingual-palatal contact, though this may be a result of the younger ages reported here compared to the previous EPG typical data in the literature (e.g. both Fletcher (1989) and Cheng et al. (2007) report on children age 6 years and older). Unexpectedly, the DS group presented with a significant negative relationship for lingual palatal contact and all target sounds suggesting that older children with DS present with lower levels of lingual palatal contact. This relationship may be explained by the presence of very low lingual-palatal contact in the two oldest speakers in the group (DS15 and DS23), particularly DS23 who shows minimal lingual-palatal contact. However, a significant relationship is also identified for the productions considered perceptually correct (which cannot be explained by DS23 who has low PTA scores for these target sounds). Cheng et al. (2007) suggest that the reduction of lingual palatal contact in their older speakers may be related to the increasing size and shape of the hard palate (as established by Hiki and Itoh (1986)). They suggest that a younger child's tongue will create more contact with a smaller palate. Speakers with DS have been identified as having smaller palates than age-matched controls but palate shapes and sizes have been noted to change with age (Škrinjarić et al., 2004) suggesting that the amount of lingual palatal contact in these speakers may decrease with age as a result of palatal shape changes, although, without any measures of palate shape, this suggestion is made with caution.

8.2.3 Descriptive EPG measures

It was suggested that EPG would provide an objective investigation of articulation patterns in children with DS. It was hypothesised (H5) that this investigation would reveal increased presence of atypical articulation patterns in sibilant production compared to TD children and adults. As there is a lack of previous studies in this area, general assumptions were based on the perceptual findings, suggesting that the results from the visual analysis of the EPG patterns would identify atypical patterns of articulation in the DS group. This hypothesis was supported with results that showed that the DS group produced significantly less typical patterns for all three target sounds compared to the TD and AD groups and all speakers with DS were identified as producing at least one atypical articulation pattern for the target sibilants. This analysis provided a detailed look at the different patterns identified for all productions of the target sounds and for the perceptually acceptable tokens. Overall, the group with DS presented with 9 more pattern types for /s/ production, and 7 more pattern types for /ʃ/ production than the TD group suggesting a high level of atypical productions. Both groups presented with patterns other than the typical pattern for both /s/ and /ʃ/, many of which did not have a straightforward relationship with the perceptual errors identified.

Both groups presented with a variety of groove widths for the target sibilants. It has been suggested that for the successful production of tongue grooving, typical speakers have a target of lateral lingual contact (Fuchs et al., 2006), which is established through a combination of auditory and somatosensory feedback (Perkell et al, 2000). It may be that the control of the lingual muscles involved in this articulation is affected by the hypotonia in these speakers, or indeed, the deficits in fine motor control. Specifically for /s/ production, the speaker is required to maintain the right balance of extrinsic and intrinsic muscles to create the narrow groove (Hardcastle, 1976). Findings showed that overall, children with DS presented with wider groove patterns (1-5 electrodes) for target sibilants than the TD or AD group (McLeod et al., 2006; Cheng et al., 2007). This suggests that children with DS may have difficulties with anterior tongue configurations, specifically the precise nature of lateral lingual contact, and maintaining lateral tension. Additionally, producing a narrow groove may be complex with a narrow palate. The high numbers of *lack of groove* and *wide groove* identified for /s/ and /ʃ/ production in both groups of children may also suggest that the limits put on typical groove width when creating the taxonomies for target /s/ and /ʃ/ were perhaps too narrow. Additionally, close examination of EPG data finds that many studies of typical speech have noted individuals with *lack of groove* articulation patterns (Liker & Gibbon, 2011; McLeod & Singh, 2008), suggesting a great deal of between-speaker variability in groove width for target sibilants. This variability may be a result of individual palate shapes, but also the interplay between groove width and other factors (e.g. sub-lingual cavity size and lip protrusion). The *lack of groove* pattern defined in 4.4.6, involved lateral bracing but no evidence of narrowing. The lateral bracing itself is probably adequate for sibilant grooving when individual palate shape and size is taken into account. In hindsight the definition of a typical groove pattern was too narrowly defined. This assumption is also backed up by the high number of these patterns occurring in the perceptually acceptable tokens of /s/ and /ʃ/ (the DS group present similar levels of these patterns after removal of the errors). It has been long established that groove width varies in speakers (Wolf et al, 1976, citing Moses (1939)) and it is probable that the pattern identified as typical for the typical /s/ and /ʃ/ articulations did not reflect that variability. Fletcher and Newman (1991) and Hoole et al. (1989) found that /ʃ/ is produced with a wider groove than /s/ and the taxonomy allowed for that difference (defining *wide groove* for both sibilants as 4 electrodes or more). However, the width definitions in the taxonomies suggested may not have been adequate.

Fronted groove was noted in the productions of /ʃ/ in both the DS and the TD group. It was expected that this pattern would be identified, following the perceptual error analysis results of *fronting*. Though the numbers are small, 7 of the DS speakers used this pattern and 3 of the TD speakers used it. Not all instances of *fronted groove* were identified as errors, however perceptually acceptable productions of /ʃ/ with a fronted tongue position are often identified in typical speech production (and will be discussed in section 8.4 below). Studies have noted that in the vowel context of /i/, fricatives such as /s/ and /ʃ/ are pulled forward in the oral cavity (Zharkova et al., 2014), which may explain the fronted position of the articulations. Perceptually acceptable productions of /ʃ/ can also be explained in typical speakers by motor equivalence strategies. For all speaker groups the anterior productions of /ʃ/ (i.e. those identified as *fronted groove)* may have been produced with an increased degree of lip protrusion (Brunner & Hoole, 2012). Motor equivalence has been well-documented in typical speech studies (Brunner & Hoole, 2012; Perkell et al., 2000; Smith & McLean-Muse, 1987) but only recently have studies shown interest in relation to disordered speech populations (though a large body of work by Perkell and colleagues (2000) have identified motor equivalence strategies for sibilant production in speakers with hearing loss). Motor equivalence strategies are identified in DS25, DS08 and DS16 who all use *fronted groove* patterns for perceptually acceptable /ʃ/. DS08 is complicated as the groove he produces is very asymmetrical therefore the *fronted groove* pattern he displays is unlike other speakers.

The groove width patterns identified are therefore not atypical articulation patterns (as they are identified in both the TD and AD groups), neither was the presence of *complete alveolar closure,* identified for both /s/ and /ʃ/. Both DS and TD groups used the *complete alveolar closure* pattern for target /s/, but only the DS group presented this pattern for /ʃ/ productions. It was expected that this pattern may relate to the auditory information (e.g. the fricatives being produced with the typical error process of stopping), and was supported by a significant relationship identified between the amount of stopping identified in the perceptual error pattern analysis and the *complete alveolar pattern* findings for /s/ in EPG descriptive analysis. However, this error has been also noted in previous EPG studies of disordered speech populations in the literature, and was not perceived as a stop (Bartle-Meyer et al. 2009; Hardcastle & Gibbon, 1997; Hartelius et al., 2005; Schmidt, 2007). For example, it is often perceived as a lateral fricative (Gibbon, 2004; Howard, 2004) or a nasal fricative (Gibbon (2004), citing Yamashita et al. (1992) and Dent et al. (1992)). These studies tend to analyse the articulation patterns after the auditory transcription (unlike the analysis here which was solely visual). It is suggested that presence of this pattern may either indicate the typical process of stopping, or the atypical substitution of lateralisation. This suggests that not considering the auditory alongside the visual information limited the analysis. Surprisingly, when analysing only the perceptually acceptable tokens, *complete alveolar closure* is still present for 14% of articulations. Although unexpected, this is not a new finding, Dagenais et al. (1994) identified complete closure in productions of /s/ and suggested that it was the result of oral cavity size, spacing of electrodes and asymmetry of the oral structures. Cheng et al. (2007) also found sporadic use of complete alveolar contact during the production of /s/ in typically developing children. This was noted in 44% of 6-7 year olds, 9% of 8-11 year olds and 42% of 12-17 year olds but Cheng et al. did not provide a theory about why this occurred. McLeod et al. (2006) noted complete closure in 10% of their perceptually correct typical AD /s/ data. They suggest that this may also be a result of electrode spacing, explaining that the narrowed airflow creating the friction for perceptually correct production is produced between electrode columns, even though the electrodes are spaced very closely together on the acrylic palate. Eight of the speakers with DS produce perceptually acceptable /s/ in this way. It may be that the narrow shape of the palate in DS affects the location of the electrodes and placement of the tongue, although, it is hard to accept that children who cannot create a narrow groove of 1-2 electrodes could configure the tongue to create an even smaller space for friction release.

The DS group presented with atypical articulation patterns for target sibilant production, for both errors and perceptually acceptable tokens. For both sibilants only the DS group present with *lateral fricative, undifferentiated gestures, articulatory drift, lack of lateral seal* and *double articulation* patterns. Only a small number of *lateral fricative* patterns were identified for the target sibilants (2% of all productions of /s/, none for /ʃ/). This was surprising as the results from the perceptual error pattern analysis identified lateralisation as the most common perceptual error pattern for /s/, and was indicated in 13% of the perceptual errors produced for /ʃ/. As noted earlier (section 4.4.3) the articulation patterns for lateral fricatives are very varied (Gibbon, 1999). The findings in this study support previous findings that identify undifferentiated gestures, complete alveolar closure, wide groove, and lack of lateral seal, retracted groove and posterior closures as patterns for perceptual lateral fricatives (Gibbon, 1990; Gibbon, 1999; Gibbon & Hardcastle, 1989; Howard, 1995; Howard, 2004; Suzuki, Dent, Wakumoto, Gibbon, Michi & Hardcastle, 1995; Yamashita et al., 1991). The lack of auditory information in this study then led to a small number of pattern types identified as *lateral* which is not surprising considering the wide variation of patterns identified for this error. The relationship between the atypical patterns and perceptual analysis is less clear. As discussed, pattern types for lateral fricatives seem to vary depending on whether auditory information is taken into account, leading to questions regarding the articulatory nature of lateralisation of /s/. This could have implications for traditional articulation therapy approaches. If perceptual lateralisation of /s/ is considered to be produced as a canonical lateral fricative articulation (as is often the case) then traditional techniques may not have the desired effect. While the mismatch of perceptual judgements and articulatory data is not a new finding (e.g. in Gibbon (1999) the author highlights the mismatch between perceptual judgements and articulatory data, noting that perceptual neutralisations may not be accompanied by identical EPG patterns), this study provides further support for the need to collect and analyse articulation data alongside auditory (and if possible, acoustic) information.

A pattern that may be perceived as a lateral fricative is *undifferentiated gesture* (UG). UG patterns were identified in only the DS speakers for both sibilants (and largely for target /t/). It has been suggested that this pattern is likely to be common in the speech of young children, relating to immature lingual control (Cheng et al., 2007; Gibbon, 1999). In this small group of young speakers there is no evidence to suggest that *undifferentiated gestures* occur in typical development, which suggests that independent control of the tongue tip/blade and tongue body has developed by age 4. Further investigations of younger children would be required to provide stronger evidence for this. However, the lack of this articulation patterns in the TD data, argues against the *delayed control* hypothesis presented in Gibbon (1999) which suggests *undifferentiated gestures* will occur in typical developing children. Therefore, these findings present support for Gibbon's *deviant control* hypothesis, which suggests that these gestures appear when the speaker is compensating for a lack of tongue tip/blade fine motor control (Gibbon, 1999). The presence of *undifferentiated gestures* also presents some contradictory evidence arguing against the suggestion that these articulation errors are widespread in individual children (Gibbon, 1999). **DS24** produces

UG patterns for all target sounds but these only appear occasionally for /t/ and /s/, although it is present for almost all productions of /ʃ/. Although the articulation patterns are varied, **DS24** shows mature levels of lingual control of the lateral borders of the tongue for /s/, however this is lacking for /ʃ/. Gibbon (1999) does suggest that children can present with discrete atypical EPG patterns (e.g. a particular articulation pattern only for sibilants). However, there is little evidence in the literature to suggest that this error appears for one target sound. It is suggested that the presence of /i/ can influence the articulation of /ʃ/, resulting in increased lingual palatal contact (Proctor et al., 2006) but **DS24** also presents with this articulation pattern with other vowel contexts (see Figure 7-18). This may suggests that **DS24** presents with problems in lingual control required for /ʃ/ in collusion with an abnormal palate shape.

The findings from the descriptive EPG analysis identified a high amount of atypical articulations patterns for speakers with DS. All speakers presented with patterns that were not the typical articulation pattern, with expected between-speaker variability. Patterns have been identified that have not been noted in studies of speech in DS so far. These findings support perceptual studies that identify atypical errors in DS (Cleland et al., 2010; Dodd, 1976; Roberts et al. 2005; Sokol & Fey, 2013), but present further evidence of atypical articulation patterns in this group, previously unidentified by auditory analysis alone.

8.2.4 Summary

Sibilant production in young people with DS shows more errors than a cognitively age-matched group of speakers. Perceptually, errors are found in the production of /s/ and /ʃ/ for all ages of speakers, with no pattern of fewer errors in older children. The speakers show signs of between-speaker variability and present with errors that are both typical (processes such as fronting, stopping) and atypical (lateralisation, debuccalisation). Atypical patterns of errors are identified in phonetic error analysis where speakers with DS have more difficulties with manner of /s/ production, rather than the typical pattern of placement errors.

The EPG measures (quantitative and descriptive) both support the perceptual findings, and provide more evidence for atypical patterns of articulation. EPG tongue-to-palate contact measures (COG and WTM) show high levels of individual variation in fricative production in DS but overall the speakers show similar tongue placement for /s/ and /ʃ/ (as measured by COG) when compared with both the TD and AD group. The relationship between the tongue placement for the two sibilants is not as clearly defined in the DS group as in the TD (which itself is not as clearly defined as the AD group).

The descriptive pattern analysis provided more information about the whole annotation and therefore the articulation patterns achieved. This analysis revealed that children with DS use a variety of patterns for productions of target /s/ and /ʃ/, and this also extends to the articulation of perceptually acceptable productions. The children with DS displayed particular difficulties with the narrow groove constriction. Even during the perceptually acceptable tokens the groove articulation was not as narrow as evidenced in the TD data. This may be a result of the narrow palate shape but may also indicate motor difficulties with tongue tip-blade articulations and control of the lateral margins of the tongue. The information provided by the pattern analysis supports growing evidence for atypical speech developmental behaviour in this group of speakers but as established, these atypical patterns do not occur in all speakers. It is suggested that the nature of the analysis (instrumental) is the reason that this study has identified more atypical error patterns than previously identified, implying that previous studies of consonant production in children with DS are wrong in concluding that children with DS present with a delayed phonological speech profile.

The lack of an age related relationship with presence of atypical patterns indicates that children with DS are presenting with articulation errors across the whole of late childhood. Considering these findings, it may be proposed that children with DS present with persisting speech difficulties (PSD: Pascoe, Stackhouse & Wells, 2006). This term has been applied to speech errors identified in children over the age of 5 or 6, who experience auditory discrimination difficulties and delayed language skills. Identifying articulation errors in DS as PSDs suggests that the application of the psycholinguistic framework of speech processing (Stackhouse & Wells, 1997) may be appropriate when considering intervention in this group of speakers. This allows for an approach that interprets the child’s strengths and weakness in terms of a speech processing chain (Pascoe et al., 2006), where breakdowns can occur at either the input or output stage (or indeed both). This approach is particularly suited to the heterogenic nature of DS, alongside the motor and auditory differences experienced in this group.

8.3 Speech motor difficulties in children with DS

8.3.1 Within speaker variability

Previous literature and findings from a smaller sample of this dataset have indicated that children with DS show higher than normal levels of within-speaker speech variability (Dodd, 1976; Dodd & Thompson, 2001; Timmins et al. 2007). Higher levels of spatial and temporal articulatory variability have been identified in typically developing young children compared to adults (Cheng, et al., 2007ab; Goffman & Smith, 1999; Green et al., 2002; Kenney & Prather, 1986; Nittrouer et al., 2005; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Zharkova et al., 2011) as a reflection of their immature speech motor skills. Therefore it was hypothesised that this group of children would show higher than normal levels of within-speaker articulation variability (H5) for the target sounds when compared to both the TD and AD groups, reflecting the speech motor difficulties in people with DS. The results partially supported this hypothesis as the DS group presented with higher token-to-token within-speaker spatial variability for all productions of the target /t/ (OSVar) when compared to the TD group and the AD group. A significant difference was reported between the DS and AD groups for sibilant production, but not the cognitively age-matched TD group. The TD group presented with a high within-speaker variability score for /ʃ/ production which may be explained by the higher than usual variability noted in typical speech development during the acquisition of a new articulation (Goffman et al., 2002). Half of the TD group still produce target /ʃ/ in error suggesting that this sibilant is yet to be acquired fully for all participants. Similarly, this may also explain the lack of a significant difference for /s/ production. As some of the TD children still present with errors in /s/ production, it may be suggested that they are still stabilising their articulations of this target sound and thus presenting with high spatial variability. However, although it has been suggested that spatial variability is influenced by speaking rate in typical speakers (Guenther, 1995), no adjustments were made to account for this influence, suggesting that more robust measures of variability are required to support this suggestion.

Dynamic spatial variability was investigated via the five case studies. The variability of the sibilant articulation across individual productions was represented by the alveolar closure score, which was calculated at 8 points across the annotations of /s/ and /ʃ/ for all TD children and the five case studies. The measurements were not quantified but presented to illustrate the variation in groove width across the sibilant articulation. Although considered stable articulations, sibilants can vary during production between the onset and offset of friction (Iskarous, Shadle & Proctor, 2008) and these are also susceptible to coarticulatory effects from following vowels (Zharkova, 2007). To investigate the suspected high levels of variability in children with DS, it was hypothesised (H10) that the speakers with DS would also present with high levels of dynamic variability in comparison to an adult mean. This was supported with a wide range of changes throughout the sibilant articulation, suggesting that these children present with dynamic within-speaker variability across segmental articulation as well as the token-to-token variability presented so far. However, these measures were compared to the AD data, not typical children. Therefore further investigations are required, particularly in light of the high levels of dynamic acoustic variability of sibilants noted by Reidy and Beckman (2014), to investigate the typical values of dynamic variability in sibilant production.

It was further hypothesised that the children with DS would present with higher levels of temporal variability than the TD group, once again reflecting speech motor difficulties (Lee et al., 1999; Smith & Goffman, 1988; Weismer & Elbert, 1982). The COV of duration measure found that, overall, children with DS were more variable than the AD group (though there was also a significant difference between the DS and TD groups for temporal variability of /s/). As noted for spatial ability above, the high levels of temporal variability for /ʃ/ in the TD group may be explained by typical variability linked to the learning of new motor sequencing tasks (Goffman, 2010). Temporal variability is found in many studies of variability in typically developing speakers, speakers with fricative production difficulties (Munson, 2004; Weismer & Elbert, 1982), and has also been noted in Brown-Sweeney and Smith (1997) for word initial consonant closure in 16 children with DS aged 7-12 (which were significantly different to their chronological age-matched control group). Therefore these findings support previous findings suggesting presence of speech motor difficulties in children with DS.

Within-speaker spatial and temporal variability, as noted for the group with DS, have previously been noted in target fricative productions of adults with Apraxia of Speech (Hardcastle & Edwards, 1992), suggesting that variability is related to speech motor difficulties as experienced in AOS. Similarly, high levels of articulatory inconsistency have been identified for Childhood apraxia of speech (CAS) (Hardcastle et al., 1987; Marquardt et al., 2004). This may support suggestions that children with DS present with difficulties similar to children with CAS.

These findings confirm previous suggestions of high levels of within-speaker inconsistencies in this group (Dodd & Thompson, 2001; Timmins et al, 2007) and support suggestions that young people with DS present with speech motor difficulties. However, unlike the word-level phonemic variability identified by Dodd & Thompson (2001) this study presents articulatory variability more representative of speech motor difficulties. Establishing the presence of phonetic within-speaker variability is vital for assessment and intervention. Zharkova (2007) notes that knowing the limits of articulatory variability in speakers without a speech disorder helps to establish range of variation acceptable for successful communication. This study supports this view, and extends this point to children with speech difficulties, specifically DS. It has been suggested that speakers with high levels of articulation variability are likely to make slow progress in therapy (Forrest, Dinnsen, & Elbert, 1997) and are later to have unresolved speech errors at a later age (Preston & Koenig, 2011; and see Pascoe et al, 2006).

Further impacts of the variability noted for sibilant production in speakers with DS is the contribution of this to listener perception. In typical adult speakers, Newman et al. (2001) found that speakers with consistent articulations for /s/ and /ʃ/ are more intelligible to listeners (based on acoustic analysis). However, applying these findings is complex in relation to children with DS who experience many other differences that impact on intelligibility (e.g. phonation, nasalisation) that are not measured in this study.

8.3.2 Relationship of age and speech variability

There is a lack of information regarding speech motor development in children with DS. It has been suggested that fine motor abilities of children with DS are closely related to their cognitive ability (Sacks & Buckley, 2003) and that motor abilities improve with age (Jobling, 1998) but this was in regard to gross motor ability. However, Spano et al. (1999) found that fine motor skills in children from 4- 14 years with DS showed little improvement with age. Similar findings were presented for oro-motor skills and age (Cleland et al., 2010). It was therefore hypothesized (H5) that there would be no link with chronological age and variability in the DS group (but there would be a relationship in the TD group).

Unexpectedly, no relationship between variability and chronological age was identified for the TD group. However, Cheng et al. (2007) also failed to find a significant reduction in spatial variability with age for /s/ production, though there was a reduction of /k/ variability, in their 36 speakers from age 6-17 years old. The lack of a relationship is not surprising as the group of speakers was small and reflected a narrow range of ages, thus speakers were possibly too similar. Surprisingly, the DS group presented with a significant negative relationship of age and overall variability of /ʃ/, (but not the TD group). This relationship did not remain when assessing the variability scores for the perceptually acceptable tokens suggesting that the older speakers may produce error-full speech but are more consistent in the errors they produce. For perceptually acceptable tokens, children with DS show higher levels of spatial variability than TD children in /t/ and /s/ production, which may be indicative of speech motor difficulties in this group which do not mature with age. There may be other reasons for variability in speech production not mentioned so far, for example, Howard (2004) notes high levels of variability in her EPG study of cleft palate speech in adolescents. She provides various explanations for this, such as sampling conditions, coarticulatory effects but also mentions the link between variability and the initiation of remediation of speech errors (citing Harding & Grunwell, 1996).

Temporal variability has also been shown to decline as children mature (Kent & Forner, 1980; Munson, 2004). Both the speakers with DS and the TD speakers in this study showed no relationship between age and temporal variability (measured by COV). As suggested above, this may explained by the small age range presented in this study and also the small number of participants. It has been suggested that in typical speech temporal variability lags behind spatial variability (Koenig et al., 2008; Smith & Goffman, 1998) which may explain the lack of a relationship between these two measures for the two groups. However, the TD group presented a significant relationship between temporal and spatial variability /t/ productions. It may be that this early acquired sound stabilised sooner than the productions of the sibilants which presented with no relationship.

In summary, there is no relationship with age and variability in the DS group suggesting a deficit in speech motor ability, and that speech motor control does not mature with age in children with DS, supporting findings from Brown-Sweeney & Smith (1997), and Bunton et al. (2007) who note speech motor difficulties in adults with DS.

8.3.3 Speech motor deficits: Sequencing tasks

In Chapter 7, five case studies were presented with extra measurements (DDK sequencing tasks) included in order to investigate a possible relationship between speech motor difficulties and atypical articulation of sibilants in DS. DDK rates have been noted to increase with age in typically developing children (Robbins & Klee, 1987; Williams & Stackhouse, 2000; Yaruss & Logan, 2002) reflecting the maturation of the motor system. Therefore it was hypothesised (H12) that these measures would identify differences in speech motor ability in the children with DS compared to the TD group, with the DS group presenting with slower rates and lower levels of accuracy than the mean TD group scores (Hamilton, 1993; Rupela and Manjula, 2010).

The results neither support or disprove the hypothesis as the case study participants presented with a variety of DDK results for rate (some higher than TD averages, others lower). In McCann and Wrench (2007), the authors reported on a larger group of speakers with DS, including some of the participants from the case studies and noted no rate differences between a group of 12 speakers with DS and a group of 4 TD speakers (aged 5;4-7;1). The TD group did not reflect the younger TD ages presented in this thesis and as a result McCann and Wrench's TD control rate data presents slightly higher scores. Nonetheless, an inconsistent finding is presented here for rate overall with some speakers presenting with faster rates than TD means in all, or some, of the tasks (DS10, DS16 and DS23). The TD data identified that multisyllabic sequencing (e.g. /pətəkə/) is performed at a slower rate than monosyllabic repetitions, however this was a pattern only evident in DS08. The other participants either show lower rates for both alternating sequencing tasks (DS23, DS10 and DS24, also noted in Hamilton, 1993) or with all tasks involving /kə/ (DS16), compared to the labial and alveolar tasks. These tasks all include a velar target which is recognised to be performed at a slower rate than alveolar gestures (Cohen & Waters, 2010; Yaruss & Logan, 2002). Overall, these findings suggest that children with DS have difficulties with alternating sequencing tasks. However, as with many results in this study, there is evidence of between-speaker variability.

Accuracy scores for the DDK tasks indicated a clearer difference between the DS speakers and TD group mean (also found in McCann and Wrench, 2007) with both the DS participants, and TD group presenting with lower accuracy for the trisyllabic task. For all tasks the DS participants presented with lower accuracy scores than the TD group mean, except DS10 who presented with high accuracy levels for lingual tasks, but labial tasks, /pə/ and /pətəkə/, had low accuracy scores, suggesting that lip movement may be problematic for DS10 (though this cannot be supported from the provided speech data in this study).

Some of the speakers presented in the case studies present with problems with sequencing regardless of the length of the target, showing a different pattern to the TD speakers. It has been noted that children with dyspraxia have no reduction in rate or accuracy in monosyllabic DDK tasks but have lower rates in the trisyllabic tasks (Thoonen et al., 1996). Specifically, Thoonen et al. (1996) suggested that monosyllabic rates of 3.5 syllables per second or more, along with problems with the trisyllabic task indicates presence of apraxia. This may suggest presence of apraxia in these speakers with DS, however the difficulties in this group extends beyond just rate differences of trisyllabic tasks.

8.3.4 Summary

Evidence from results presented here suggests that EPG measurements have identified higher than normal levels of spatial and temporal variability for sibilant production in speakers with DS than previously reported (Brown-Sweeney & Smith, 1997). Articulatory variability analysis has not been performed on a large group of children with DS in the past and these findings can help add to the growing literature suggesting that young people with DS show higher than normal levels of inconsistency in speech articulation. This is not related to their overall speech ability with some speakers showing high variability but low perceptual errors. The presence of this variability, alongside atypical articulation patterns, demonstrates that children with DS have difficulties with speech motor control (Goffman, 2010; Kent, 1976), and specifically, difficulties controlling the functional parts of the tongue (Hardcastle et al., 1987).

Variability was also identified in the dynamic articulation of the fricative, suggesting that the control of the articulators is unstable. This suggests a different pattern to the TD group, but there is a lack of research in this particular area so any assumptions are made with caution. As with all measures in this study, individuals were also found to present with very different levels of variability. Further investigation of dynamic articulation patterns is required, as individuals present with small alterations to a normal stable articulation patterns across the friction

To conclude, EPG measures of spatial articulation patterns in sibilant productions have identified evidence of speech motor difficulties in children with DS by providing measures of spatial and temporal variability, inaccuracies of DDK measures and dynamic articulatory instability. Presence of variability in speech production has been suggested to reflect a lack of underlying phonological representations for target sounds (Macrae, Tyler & Lewis, 2014). Similarly to variability, it has been noted that in typical speech acquisition categorical representation of speech sounds increases with age. There is no indication in this study that age has an impact on variability therefore it may suggest that these children do not present with a delayed development of categorical representations, but an atypical categorical representations. It was suggested above (section 8.2.2) that the problems with auditory feedback in this group may have an impact on underlying representations.

The difficulties with speech motor control in this group may be explained by the application of Perkell and colleagues' theory of speech motor control (2000). In this model the authors suggest that speech movements are dependent on auditory and tactile feedback that allows speakers to produce articulations that achieve an acoustic goal (e.g. motor equivalence strategies). Additionally, speakers with high levels of auditory acuity and tactile feedback present with more perceptually distinct sibilant contrasts. The data provided above suggests that some speakers with DS adapt their articulators for an acceptable sibilant production, but many others produce atypical articulations with unsuccessful results. It may be suggested that children with DS present with auditory feedback difficulties as a result of hearing difficulties that contribute to problems acquiring an appropriate acoustic goal. However, if we assume that tactile feedback (or somatosensory feedback as suggested by Ghosh et al., 2010) is important for sibilant production for these speakers then the presence of an EPG palate during speech production may have also had an impact on successful articulation. At this stage is it difficult to provide a confident conclusion regarding this theory and children with DS. Further investigation and analyses regarding perception and somatosensory skills is therefore required.

8.4 Articulation patterns for perceptually acceptable sibilants in children with DS

8.4.1 EPG analysis of perceptually acceptable sibilant production

Although it has been suggested that sibilant fricatives require a stable articulation and cannot support a wide range of articulations for perceptually acceptable tokens (Dagenais et al., 1994; Dromey & Saunders, 2009; Fuchs et al., 2006), evidence from both the quantitative and descriptive EPG measures indicate presence of lingual-palatal contact patterns not expected for perceptually acceptable productions of target sounds.

Both the COG and WTM presented similar patterns of scores for sibilants once the errors had been removed from the analysis. For example, COG scores for /s/ and /ʃ/ were still less distinct for the speakers with DS, compared to the TD and AD groups. Similarly, the WTM scores presented a similar picture without errors as presented for overall measures. It was hypothesised (H14) that due to the precise nature of sibilant articulation that the TD group would present with typical articulation patterns for perceptually acceptable productions but the group with DS would show atypical articulations (see Lee et al., 2013). Unexpectedly the TD group presented with a wide range of patterns for perceptually acceptable sibilants. The DS group presented with almost all patterns from the taxonomy for target /s/ (not *undifferentiated gesture, lateral fricative, affricate* and *articulatory drift*). Similarly, the DS group presented with evidence of all pattern types from the taxonomy for target /ʃ/ (not *minimal contact, undifferentiated gesture*, and *anterior closure with lack of lateral seal).* Individual pattern types have been discussed in section 8.2.3 above, in relation to DS and TD perceptually acceptable productions.

The identification of a variety of productions for perceptually acceptable tokens in the DS group is an important finding and suggests that although we have a growing number of studies of typical speech production using EPG, we cannot apply the same articulation targets to individuals with DS. Recent investigations of children with speech sound disorders (Lee et al., 2013) have identified the similar phenomenon in the production of perceptually acceptable /t/ and /k/. They found that the children with SSDs had significantly more contact for perceptually acceptable /t/ than their TD comparison group. Gibbon (1999) also notes that perceptually acceptable productions in children with articulation and phonological disorders did not produce similar EPG patterns to typically developing speakers. The results from Lee et al. (2013) and the various findings here for perceptually acceptable tokens highlight the need for further investigations regarding articulatory variation. Similarly, Hardcastle et al. (1987) identified patterns of retracted closure and double articulations in perceptually acceptable tokens of alveolar plosives in children with Childhood Apraxia of Speech (CAS). In her study of speakers with CAS, Kocjančič (2010) analysed tongue positions using Ultrasound analysis and also noted qualitatively different tongue patterns for perceptually acceptable productions. Her visual analysis of articulations found that the tongue movements were more limited than those of TD speakers which led her to conclude that the same acoustic properties of speech sounds are achievable with slightly different tongue positioning. The children with DS in this study experience many obstacles when attempting precise tongue configurations. The explanation for the range of different patterns for perceptually acceptable tokens could be a combination of speech motor deficits and structural abnormalities, resulting in a need for atypical articulatory constrictions for perceptually acceptable productions. Additionally, the interpretation of a groove to be typical (narrow) may obstruct a wider articulated groove in a speaker with a high narrow palate. These factors may all contribute, but considering findings from Lee et al. (2013) and Kocjančič (2010), who analysed speakers without structural abnormalities and also identified a variety of patterns, this may present evidence of a speech motor deficit.

Overall there is clear evidence for atypical articulation patterns in children with DS compared to a cognitively aged-matched group of typical children. However, this analysis has also raised questions about the variability and ranges of articulations used in perceptually acceptable speech production for children with speech disorders. Understanding the variability of individual articulation behaviour for perceptually acceptable target sounds has wide implications for intervention, suggesting that planning and targeting cannot rely on typical standard articulation information.

The articulatory pattern data for perceptually acceptable sibilant production from the TD participants raises similar questions regarding the nature of sibilant acquisition and what is considered acceptable for typical articulation. Studies agree that adult speakers can show between speaker variability of articulation patterns (e.g. McLeod et al. 2006). However, little EPG information is available for young typical children (i.e. under 6 years). The descriptive EPG pattern analysis presented a variety of previously unidentified pattern types for all target sounds analysed. Although the TD speakers present with *typical patterns* for the majority of the perceptually acceptable sibilant productions, they also produce a variety of other patterns including: *complete alveolar, wide groove, lack of groove, fronted groove, anterior groove and velar constriction* and *affricate* (some of which are discussed in 8.3.2). The presence of these patterns recalls findings from Li et al. (2007) who suggested that instrumental analyses of sibilant fricatives in young children shows "that sounds that are all transcribed as /s/ in IPA can be phonetically very different" (pg. 919). As discussed in relation to *double articulation* in section 8.5.2., findings from this study and those identified in Li et al. (2007) suggest that typical speech acquisition presents with different articulatory stages. Moreover these findings support the need for instrumentation to fully understand the developmental trajectories in typical speech (Li et al., 2007).

8.4.2 Relationship between perceptual and pattern analysis

The EPG descriptive analysis presented a variety of different articulatory patterns for the target sounds in this study. Often, the perceptual and pattern analysis relationship did not always align closely. This may be expected as EPG presents lingual-palatal contact only and as such does not present a complete picture of speech sound articulation. However, previous accounts of sibilant production in typical speakers have noted a close relationship between articulatory (EPG) measures and acoustic measurements (Hoole et al, 1989; Tabain, 2001). The findings from these typical studies do not agree with findings regarding the misalignment of perceptual and instrumental articulatory information as identified in disordered speech studies (Howard & Heselwood, 2011).

In this study the measure of PTA and % typical pattern identified a relationship only for /t/ in the group with DS, and /ʃ/ for the TD group. As mentioned above, the lack of correlation for the sibilants is not unexpected as the descriptive pattern analysis was a measure of lingual palatal contact only, also some of the patterns provided as *other* for the sibilants may have been more typical (e.g. *lack of groove* and *wide groove)* than previously thought. In order to investigate this Spearman's Rho correlations were run on the PTA scores and the typical pattern scores for the sibilants, this time including *wide groove* and *lack of groove.* As expected, the inclusion of these patterns as typical articulations results in a significant relationship between the perceptual results for both sibilants (PTA scores) and the pattern analysis for the DS. This suggests that the standard patterns identified for typical /s/ and /ʃ/ should be reconsidered to include wider grooved articulations (particularly when applying these taxonomies in further studies), but also that perceptual and EPG information aligned closely for all groups.

Results from this study support findings that identify motor equivalence strategies in typical speakers and additionally, identifies presence of this in children with DS. Ultimately though, evidence of these adaptations is beyond the analysis scope of EPG which does not differentiate between parts of the tongue, or provide information from the lips.

The relationship between the atypical patterns and perceptual analysis is less clear. As discussed above (section 8.2.3), pattern types for lateral fricatives seem to vary depending on whether auditory information is taken into account, leading to questions regarding the articulatory nature of lateralisation of /s/. These findings suggest that although EPG can provide important articulatory information, this should not be considered independently of auditory information. Perceptually, speakers with DS present additional difficulties with prosody and voice which can impact on the overall perception of a speaker. As Howard and Heselwood (2011) argue, these levels of phonetic information do not need to be in competition with each other, but can provide supportive detail of both listener and speaker information.

8.5 Other findings

8.5.1 Between-speaker articulation variability in individuals with DS

It was hypothesised that perceptual (H2) and EPG measures (H5) would provide evidence of between-speaker variability in the speakers with DS. Further evidence for between-speaker variability was expected from the case studies (H6). As established in the literature (Rupela et al., 2010), children with DS present with high levels of between-speaker variability in comparison to cognitively age-matched TD children. Kumin (1996; 109) notes that children with DS have "varying rates of progress in communication, language, and speech development", and this study supports this claim. The between-speaker variability suggests that it may be difficult to generalise the articulatory findings to a wider group of speakers with DS. These findings also suggest that small group studies of speech behaviour in people with DS are at risk of misrepresenting the overall abilities of this group.

High levels of between-speaker variability in EPG measures of sibilant production indicates that therapy target patterns must be tailored to each individual in terms of tongue-palate contact. Awareness of the lack of homogeneity in children with DS can have an impact on clinical decision making and planning of future research.

8.5.2 Articulation patterns for target stop productions in TD children

The main aim of this study was to provide detailed articulation information on the production of target voiceless sibilants in children with DS in comparison to TD and AD speakers. One of the additional findings from this study was the range of patterns identified for target stop production in all speaker groups. As noted above, the TD children presented with more atypical patterns for sibilant production than expected. It is suspected that these findings related to the age range presented in this study compared to typical EPG data previously reported (3;8 years to 7;1 years compared to 6 years upwards in Cheng et al., 2007).

For /t/ production the TD group showed the following patterns: *incomplete closure, retracted articulation, double articulation* and *anterior closure with lack of lateral seal* for perceptually acceptable productions. While these are noted in other studies (and discussed above, 8.2.3), it is important to highlight that these patterns are not provided as typical or standard patterns when using EPG for intervention and indeed there is a lack of EPG information from typically developing children. A surprising finding was the presence of the (alveolar-velar) double articulation pattern in the TD data which occurred once during the production of target /t/ for the youngest participant (TD32, 3;8 years). Double articulation patterns for target alveolar or velar sounds have been identified in speech disordered populations via EPG analysis (Dent et al., 1992; Hardcastle et al., 1989) and have not been identified for target consonants in EPG studies of typical articulation to date. However, Gibbon (2004; citing Harding & Grunwell, 1993) notes that auditory evidence exists for presence of double articulations in typical development. In EPG intervention studies targeting velar fronting, double articulations have been identified as an unperceivable sign of articulatory change in the client's productions. It may be for TD32 (and for all typical children) that double articulation is a normal artefact of typical speech development reflecting the onset of maturation of independent lingual control. The presence of this pattern in the TD data raises questions about our understanding of typical articulation patterns involved in early stages of speech acquisition. If children initially lack independent control over tongue tip and body (Kent, 1983) then perhaps alveolar-velar double articulations are an in-between stage before this control is established. These findings support suggestions from Li (2008) regarding early lingual acquisition in typical children. Li (2008) states that covert contrasts in early sibilant production provide evidence of initial undifferentiated gestures, adding that this indicates that children do commence speech acquisition by producing well-formed categories. Li's participants were slightly younger (2-3 years) than the TD children in this study, however patterns identified here may relate to a slightly later stage of lingual development. Though as Li's study did not use EPG, it is possible that double articulation patterns were also being used by her participants.

The other patterns identified for target /t/ (and all heard as perceptually acceptable productions) were: *incomplete closure, retracted anterior closure* and *anterior closure with lack of lateral seal.* Some of these patterns have previously been identified in studies of typical children using EPG. *Retracted anterior closure* describes the usual horseshoe shaped pattern of articulation for target alveolar stops but retracted from the alveolar place of articulation. As noted with *double articulation,* this pattern was only identified in TD32. Retracted articulations in TD speakers were identified in Cheng et al. (2007) for their younger speakers, with a trend noted for an increasing forward tongue placement demonstrated in relation to age. While this pattern is reflected in this group of TD speakers, the age ranges are different to Cheng et al. (2007) who report this pattern for children 6 years and older. Similarly the presence of *incomplete closure* for /t/ production was also identified in Cheng et al. (2007) who noted this in their older speakers (12-17 year olds and adults). This pattern was identified for two of the older speakers in this TD group (aged 6;9 and 7;1). Cheng et al. (2007) suggest that this pattern may be a result of a more anterior place of articulation where the lingual contact is placed on the front teeth. Similarly, McLeod and Singh (2009) provide maximum contact frames for typical adult productions of /t/ that show *incomplete closure* which they also suggest is a result of lingual contact with the teeth.

It may be suggested that the patterns identified for /t/ reflect the robust nature of plosive articulations, where productions can withstand variations in articulations without it impacting on the perceptual information. Dagenais (1995) has suggested that plosive sounds are more susceptible to variation as they do not require the precise articulation demanded from fricatives. In her EPG study of typical /n/ production, McLeod (2006) found high levels of between- and within-speaker variability of lingual-palatal contact and suggests that this may be related to a wider range of acceptable articulations for the same acoustic result. Additionally, based on their /t/ and /l/ EPG data, Cheng et al. (2007) suggest that the range of tongue placement for production of anterior consonants is larger than originally believed. This finding is supported by Fuchs et al. (2006) who claim that the tongue collides with the palate during stop production, in contrast to the accurate placing of the tongue along the lateral planes required for fricative production. This suggests that articulation patterns for typical production of plosives may require more analysis to establish the range of patterns for acceptable productions in typically developing children.

8.6 Other factors affecting sibilant production in DS

8.6.1 Hearing loss

All of the children who participated in this study were recruited with no substantial hearing loss. This does not discount the impact that previous hearing loss may have had on their speech development. Considering the prevalence of OME in DS it is likely that some of these children experienced high levels of hearing loss during important stages of speech acquisition and development that may have negatively impacted on their articulation development (Laws & Hall, 2014). It may also be considered that auditory difficulties in children with DS would affect auditory feedback considered vital for successful sibilant production (Perkell et al., 2004).

8.6.2 Palate shape and tongue size

Without clear measurements of both the hard palate and the tongue in these speakers, it is hard to conclude that the anatomical differences play a part in the speech difficulties noted here. Articulation information from the analysis of lingual-palatal contact shows that almost all speakers in this study are able to create a narrow groove at some point during their attempted productions of /s/ and /ʃ/. It may be that the children with DS are able to adapt their articulation patterns to compensate for the structural differences, which would explain the different articulation patterns identified for perceptually acceptable productions.

Although lacking in actual measurements we can consider the relationship between measurements in this study and previous findings of palate shape and size in DS. For example, seven speakers in this study were perceived to use lateral misarticulations for /s/

production (DS04 and DS34 for all repetitions). This increased lingual contact may be a result of the relatively large tongue in contrast with a narrow palate. Although previously suggested that palate shape and size can influence articulation variability, this study cannot provide any similar links for these participants without actual palatal measurements.

8.6.3 Dentition

There was little information to be analysed with regard to dentition in this dataset but for two speakers that were analysed in detail in the case study (sections 7.2.3 and 7.4.3), the malocclusions that they had did not seem to have a specific impact on their speech behaviour. Considering the importance of dentition on the production of the sibilant fricatives, and the presence of dental malocclusions in this group this was a surprising finding but as established in Chapter 2, there is no definite link between malocclusions and speech errors.

8.7 Critical review of the investigation and directions for future research

8.7.1 Limitations of the data set

This PhD study was only possibly because of the MRC funded project ‘Assessment and Treatment of Impaired Speech Motor Control in Children with Down’s syndrome’ (MRC Grant number: G0401388). However, basing a PhD study on a dataset originally designed for a different set of research questions, by a different academic team is limiting. Although the PhD researcher was a member of that team, many decisions regarding data collection were made prior to her involvement.

The dataset that was available for analysis was useful as it provided clear EPG and acoustic recordings of two problematic speech sounds that could be analysed successfully using EPG. However, the amount of data was compromised by the many different aims that the MRC wordlist (that the speech analysis in this PhD is based on) was targeting. These included /s/-cluster environments, multisyllabic word, sites of coarticulation (see Table 8-2 below).

If the dataset had been designed for the purpose of this particular study then information on the voiced equivalents of the target fricatives would have been collected for analysis, along with a range of vowel contexts. These would have included more open vowels (particularly for target /ʃ/ which is followed by a high front vowel in this study) and rounded vs unrounded vowels. Open vowels would be an ideal environment for consonant analysis as these have little lingual-palatal contact which would have made annotation of productions easier. A range of vowel environments may have provided some more information about whether speakers with DS display characteristics of CAS as vowel errors are one of the identified articulation features of CAS.

Wordlist item	target sounds
a toe	WI /t/
a sun	WI /s/
a clock	WI /kl/
	WF /k/
a sheep	WI /ʃ/
a chicken	WI /ʧ/ WM /k/ WF /n/
a red car	/dk/ coarticulation
the slippers	/sl/ cluster
a helicopter	multisyllabic word

Table 8-2: MRC Project wordlist

8.7.2 The control groups

The PhD study would have benefitted from a TD group that was matched by chronological age in order to assess the impact of structural differences on variability and articulation accuracy. As no palate measures were made, the assumption is that the TD control group had smaller vocal tracts to the DS group due to age impact (as well as genetic differences) which made it harder to compare the groups, though this may not be the case considering the size and shape of the upper palate in DS. The PhD researcher did not approach a further group mainly in consideration of the low uptake of TD participants in the initial group and also due to financial constraints (acquisition of EPG palates).

8.7.3 Lack of dentition information

As this particular study was born of a larger study, the data was collected prior to the methodological considerations for the PhD study. At the onset of the MRC study, dentition information was considered a desirable aim for all participants. This data was only provided for a handful of speakers. There were a couple of reasons behind this, one was that while the orthodontist involved in the project was highly accommodating with our patients it did impact on his time so there were limited opportunities for the dental information to be noted. The orthodontist himself found our prepared form to be inaccurate and difficult to use. At that point in time it was decided to remove this analysis.

In hindsight this was a missed opportunity. Considering the detailed analysis of the articulation of these specific sounds, detailed dental information would have been a particular asset to this study.

8.7.4 Lack of palate shape/structure information

A further limitation to this study was the lack of palatal measurements. As previously discussed, a growing body of work in typical speech production has found that palate shape can affect the articulation distinctions for individuals. As a group with recognised palate structural differences, and high levels of between-speaker phenotypic variability, individual measurements would have been a strength of this study. This data would have provided an opportunity to correlate differences in palatal structure and articulation. Based on the experiences in this study, it is recommended that further research concerning speech articulation errors in DS analyses hard palate shape and size, and provides supplementary articulatory measurements (e.g. Ultrasound).

8.7.5 Analysis limitations

8.7.5.1 Perceptual analysis limitations

When performing the perceptual analysis the SLTs were instructed to analyse the provided data using broad transcription. It has been shown (particularly in Chapter 7) that this is insufficient for this group of speakers. Many of the errors identified by EPG analysis were not identified by the perceptual analysis, which led to some confusion when interpreting the articulatory information. The manner of transcription was decided early on as a means to provide a measure of a percent consonants correct calculation as is usual in standardised SLT assessments. As the analysis progressed it became clear that a narrow transcription would have been more suited to this research. It is with hindsight that the researcher believes a narrow phonetic transcription of these productions (as suggested by Ball, Müller, Klopfenstein & Rutter, 2009) would have been beneficial to this study. The EPG information and analysis can help to provide detailed information about lingual-palatal articulation in this population but does not capture the many other dimensions of atypical speech behaviour that may impact on successful fricative production.

Additionally, the categorisation of an acceptable production of a target sound was also complicated. Both clinical and sociophonetic considerations were made for this task. The local accent was Scottish English so accent variation was considered. For the WI consonants produced there are not many socio-phonetic variations which made the phonemic categorisation relatively straightforward. However, the obstacle here was related to the decisions made by a clinician when considering a production to be typical of the target sound and therefore considered to be perceptually acceptable. As the PhD researcher is not a trained clinician, at points of confusion or uncertainty the PhD researcher consulted with SLT colleagues who could advise accordingly. One particular area of uncertainty was with the production of affricated plosives (where the release stage of the plosive is slower than usual and a small degree of friction is audible). It occurred to the researcher that the presence of affrication in these productions was indicative of a motor difficulty but the overall presence of affrication was not considered by clinicians to be something that would be considered unacceptable. There is little information about the presence of affrication in the local dialect though Jane Stuart-Smith has noted affrication in the speech of older speakers of Glaswegian (personal communication).

Classifying sounds into phonemically acceptable categories is limiting and should also be backed up by some further analysis that either explains the nature of the errors (as in detailed substitution categories such as provided in Roberts et al., 2005) or provides articulation information with instrumental analysis. Establishing the nature of speech difficulties in DS is limited by phonologically based perceptual analysis. In categorising errors the researcher misses fine phonetic details that indicate an instability or inaccuracy that is consumed by the phonological categories. Perceptually we see pre- and post-affrication of plosives, pre-aspiration of plosives and fricatives, retraction in place of articulation, however, these features were not sufficiently different to create a different perceptual phonemic categorisation.

8.7.5.2 Limitations of analysis techniques

As mentioned above (8.7.1), the data provided from the MRC Project produced EPG and acoustic information for auditory and instrumental analysis. The initial intention was to analyse and discuss findings from acoustic data alongside perceptual and EPG analyses. A decision was made to withdraw this level of analysis, but to consider the data for future investigations. Acoustic analysis would have provided another level of articulatory information not available from the EPG analysis such as information on voicing, nasalisation, affrication, aspiration and lip rounding, and would have provided a fuller picture of the sibilant production (in addition to the lingual-palatal contact). In particular cases the acoustics may have identified presence of nasal and lateral friction, not noted in the EPG patterns. Further work with this dataset should aim to investigate the relationship between groove width and acoustic measurements in light of findings from Shadle, Fletcher and Newman (1991), who identify a relationship between high frequency measures, narrow groove and perceptual distinction of /s/ and /ʃ/.

The auditory analysis was based on pre-recorded sessions with audio information only. Although audio recordings provide the researcher with a much better quality of sound (Perkins & Howard, 1995) compared to video recordings, although it should be noted that digital recording technologies have improved over the past twenty years, visual information is unavailable. No video recordings were available for this group of speakers but considering the nature of the speech sounds analysed, video data would have been beneficial for interpreting the level of lip rounding involved in the production of the target sibilant fricatives (particularly for the interpretation of motor equivalence strategies). Perceptually, Stephens and Daniloff (1977) suggest that the identification of sibilant errors is more successful when live, or when video recordings are used.

8.7.5.3 Pattern analysis

The pattern analysis provided a detailed look at the lingual-palatal ability of young people with DS, articulating the target sounds /t/, /s/ and /ʃ/. This type of analysis is highly subjective and ideally requires more than one transcriber to categorise these complicated patterns of articulation, this was not available for this study. The annotation regions that the analysis was based on did not always provide a straight-forward category of articulation and some annotations displayed more than one pattern type. Perhaps unfortunately, these double (or triple) patterns were ignored in favour of a more simplistic categorisation technique. The categorisation was based on the pattern used for the majority of EPG frames in the annotation. This was considered preferable to analysing pattern types from one point in the annotation (as is done with the quantitative EPG measures). In future, both methods could be used.

It is difficult to assess whether this visual approach is beneficial, or not, in the analysis of articulation ability and variability in this group. The visual analysis looks entirely at the lingual-palatal contact without any interference from the auditory system. However, listeners and speakers do not process speech in this way so the patterns should always be interpreted with the auditory information alongside. In this case, lateral articulations of target sibilants were identified from the perceptual analysis but not consistently from the visual pattern analysis. As suggested in Howard and Heselwood (2011) instrumental analysis can provide information regarding the nature and range of articulations, but without an auditory-perceptual record, it will not be known what it sounded like.

Another important point to consider with visual EPG analysis is that the electrode spacing is normalised. This is particularly important when discussing groove width in fricative production. For these analyses, actual measurements of the groove width created (e.g. in mms) would provide a more reliable set of results Similarly, the information gained from lingual contact with the EPG electrodes is lacking in regards to pressure of contact (though see Murdoch (2010) for advances in this area). Finally, the lack of lingual contact can only visually be interpreted as a lack of lingual constriction, though there is no reason why the speaker may not be attempting to create the precise lingual configuration, albeit without the palatal contact. This lack of lingual information is limiting particularly in the investigation of a group of speakers with muscle hypotonia which may affect articulatory pressure.

8.7.5.4 Canonical analysis

The Canonical Analysis measurement provides a way of comparing the overall EPG articulation pattern with a modelled, standard version of target sounds. In this study, the attempted productions of /s/ and /ʃ/ were compared to normal/standard EPG patterns for /t/, /k/, /s/ and /ʃ/. Canonical analysis provides a comparison measurement that is hard to quantify and analyse for descriptive purposes, however it would be of great benefit to studies requiring pre- and post-therapy measures as it can help to capture movements towards or away from a target production.

8.7.6 EPG advantages and limitations

The use of EPG in this study has contributed phonetic detail regarding speech articulation in both DS and cognitively age-matched typically children that has not been available in the past (though see Hamilton, 1993; Timmins et al., 2007, 2009). This technique has presented evidence of within- and between-speaker variability in fine detailed articulation patterns of sibilant production. Patterns of articulation behaviour such as double articulations, undifferentiated gestures, and increased lingual contact have been highlighted for acceptable productions of English coronal speech sounds that would otherwise be missed in traditional auditory analyses.

However, EPG does have its limits. As an imaging technique that records the timing and location of tongue contact on the roof of the mouth during speech production (and other non-speech oral tasks) it does not, by definition, provide information about the tongue itself. This means that the information gained about tongue contact can only accurately detail what part of the oral cavity is in contact with the tongue, not what part of the tongue is involved in that contact. For this study it has not been a serious limitation, though at times a picture of the tongue shape underneath the contact would have been interesting. Stone and Lundberg (1996) note that the tongue shape differences may not be reflected in tongue-palate contact differences (particularly in the /s/~/ʃ/ distinction). There is also lack of confirmation about tongue contact with the teeth (which can only be speculated from the pattern analysis interpretation). This can be important in the investigation of sibilant production particularly as many of the pattern types identified were considered to be produced with lingual-dental contact (without concrete information that this was the case).

Other aspects of articulation that may be of interest for this population, and not identified in EPG data capture is the pressure of contact involved in the lingual-palatal connections. The system may interpret any light contact in the same way as a confident strong articulation. Additionally, EPG does not recognise levels of lingual-palatal proximity. These near contacts may be of great importance for interpretation (particularly in this group of speakers) of articulatory targets.

8.8 Directions for future research

The findings in this study have provided further evidence of atypical speech production in children with DS and the speech motor difficulties that contribute to these. Further research is required to establish how these speech motor difficulties and atypical speech productions develop in these speakers and also to establish the impact of structural differences on these productions. Further analysis of the speech motor abilities in these children should strive to provide a longitudinal EPG study of speakers to establish the developmental changes in young people with DS. This would help the comparison with the large amount of research on maturation of speech ability and motor skills in typically developing children.

Following work by Brunner and colleagues for typical speech production, a speaker-specific study of palate shape and fine phonetic ability is required to assess the impact of these differences on this group. In tandem, actual measurements of groove widths created for these target sounds would possibly provide more information about the control of the tongue tip/blade system in speakers with DS. This could potentially involve the coordination of ultrasound and EPG information, to further establish the relationship between articulation constriction and palatal shape.

A specific area of study would be to establish the dynamic pattern of /s/ and /ʃ/ production in typically developing children and explore the complexities of the groove configuration in these children. These measures could then be applied to a quantified set of data of groove pattern dynamics in children with DS.

Another under-researched area of interest for speakers with DS is articulation behaviour within connected speech. The speech data in this study was limited to single word productions which are considered to have an "uneasy relationship with real speech production" (Howard, 2007). Single words, as used in this study, are easy to elicit but cannot be generalised to speech intelligibility. Intelligibility is significantly reduced in children with DS. However, this evidence is often acquired from parental reports (Kumin, 1994). Furthermore, it has been noted that children with DS have more articulation errors in complex syllabic productions and conversations (Iacono, 1998; Rupela & Manjula, 2007). There is clearly a need for instrumental analysis of speech productions within connected speech. A small study of assimilation in this group of speakers with DS (Timmins et al., 2008) identified a lack of coordination in children with DS compared to a TD control group. However, more speakers and measurements are required to make more concrete claims about the coordination skills speakers with DS display beyond the word level, and additionally the interplay with prosody.

An interesting finding from this research was the range of articulation patterns identified in both the DS and TD groups. The findings from the typically developing dataset indicate that future EPG analysis could provide more insight into the motor ability and changes that occur during the typical acquisition of speech. Typically EPG studies have analysed the speech of children from the ages of 6 years upwards. However, in this study, children as young as 3yrs 8mths provided clear EPG data for comparison. From the small number of speakers involved in this study is it evident that there are patterns of typical articulation and acquisition that have not been identified in previous EPG studies to date. Similarly, there is a need to understand the normal range and variability of perceptually acceptable tokens in speakers with speech difficulties as the factors limiting their overall speech production may alter the articulations they produce for an acceptable acoustic output. It would be worthwhile to investigate what range of articulations are produced in auditorily acceptable productions in both typical and atypical speech populations. Along with work by Lee et al. (2013), this study has begun to fill in our gaps of knowledge in this particular area and it is suggested that this is an important area of study that will help clinicians understand the range of articulation variability that their client may be working with in remediating speech production errors.

8.9 Summary and Conclusions

This study continued on from case study work presented by Hamilton (1993) and Gibbon et al. (2003), providing detailed articulation information about a group of speakers with wide ranging difficulties and abilities, and presented the first detailed articulatory analysis of sibilant production in young people with DS. Using Electropalatography and a combination of quantitative and descriptive measures, a picture of the typical and atypical articulatory strategies was discovered. In addition to providing a very detailed look at articulation difficulties in DS, this study also provided information (as well as some initial data) regarding the range of typical articulation patterns encountered in typical speech development.

In the background chapter the study presented information about the particular differences that people with DS experience that have been suggested to affect speech production and development. An overview of the communication abilities and difficulties of this group was then presented alongside information about typical speech production, development (and typical errors during this process). The chapter then narrowed its focus to one particular area of speech difficulty in DS, sibilant fricative production, with information from studies of typical development and atypical speech populations. The chapter concluded by reviewing the benefits and reasons for further assessment of these speech sounds using instrumental speech technology, in this case Electropalatography.

The methodology section was split into 2 parts. The first part provided an explanation of background to this study, in particular the MRC Project, the participants, the data collected and a detailed look at the various perceptual and EPG measures employed in the study. The second methodology section presented new taxonomies of articulation patterns identified in the speech production of these particular children with DS.

The results were presented in 3 sections. The main findings of the thesis are summarised below:

> Perceptually, children with DS show significantly more errors in sibilant fricative production than a group of cognitively age-matched children. The perceptual analysis of individual speech sounds indicates a higher presence of atypical errors than previously indicated suggesting that the speech development of young people with DS does not follow a straightforward delay pattern. Kent (2000) suggests that impairments of both phonology and speech motor control may coexist in some speech and language disorders and this is probably the case for children with DS.
>
> Spatial variability measurements indicate higher levels of token-to-token variability in children with DS, compared to both children and typical adults. There is no relationship between levels of variability and perceptual accuracy for children with DS, neither is there any impact of age on overall variability, suggesting that speech motor abilities do not mature similarly to typically developing children. Individual speaker variability of lingual-palatal contact is also evident in COG and WTM scores. This leads to suggestions that speech in children with DS is inconsistent, reflecting atypical speech motor skills.
>
> Furthermore, temporal variability during sibilant production is high for the children with DS in comparison to typically developing children. This is evidenced via measures of variability of segment duration and instability of groove width

during sibilant production. This also supports suggestions that children with DS present with speech motor deficits.

Lingual-palatal measures of articulation find that children with DS produce /t/ and /s/ in a more posterior position than typically developing children but that they maintain the appropriate placement distinction between /s/ and /ʃ/ production. Overall the children with DS show a smaller placement distinction between /s/ and /ʃ/ than the other two groups (for overall production measures, and perceptually correct tokens).

Spatial articulation information shows that children with DS produce target sibilants with a variety of atypical articulations, for both perceptually correct and incorrect productions. This finding further highlights the atypical nature of speech production in this group, and many articulation patterns identified are evidence of speech motor control deficiencies and structural differences in children with DS. This analysis process also unearths previously undetected articulation patterns for target sibilants in the typically developing control group. Specific information about tongue tip-blade control was provided via detailed analysis of sibilant groove production, highlighting the difficulties with fine motor control in specific speech tasks.

The pattern analysis results in 6.2 support the perceptual findings and provide evidence of atypical patterns for perceptually acceptable tokens, thus illustrating the limitations of perceptual analysis in complex speech disorders. While perceptually the listener may categorise the production as a typical substitution, the production may show signs of atypical articulation patterns hidden to the ear. This may explain the overall assumption that children with DS display a delayed developmental disorder. Perceptually this may be the case, but the articulation may show signs of atypical patterning (e.g. undifferentiated gestures, double articulations). This study has found evidence in some speakers that there are atypical articulation gestures masked by categorical perception. This is a frequent finding in EPG studies of speech disorders and is not unexpected in this group of speakers.

Specific speech motor tasks (DDK) show that children with DS show lower level of syllables per second for trisyllabic DDK tasks in comparison to TD norms. Again, individual variability is apparent for these measures. Comparisons with studies on DDK performances in CAS find similarities in these speakers, suggesting a possible presence of CAS but more information is required.

The case study chapter presented 2 children with different dentition abnormalities, detailed examination of their articulation patterns found no adverse effect of dentition and speech ability.

Finally, this thesis provides information from a wide range of speakers with DS who present with different articulation profiles. These profiles show signs of developmental and non-developmental errors but importantly highlight the pressing need for articulatory analysis in this group. Using EPG in the specific analysis of fricative production has increased our understanding of speech motor abilities in this group of diverse speakers.

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Appendices

Appendix I: Allocation of tasks

Task	Researcher
Data collection	DS: Research SLT
	TD: PhD researcher & research SLT
	AD: PhD researcher
Data analysis	Perceptual: PhD researcher & research SLT
	EPG: PhD researcher
	DDK: DS: research SLT, TD: PhD researcher
Taxonomies (creation of)	/t/: MRC project team
	/s/: PhD researcher
	/ʃ/: PhD researcher

Appendix II: Participant Consent Forms

Queen Margaret University College
EDINBURGH

Participant Identification Number:

CONSENT FORM

MRC Research Project: Assessment and Treatment of Impaired Speech Motor Control in Children with Down's syndrome.

Please initial box

1. I confirm that I have read and understood the information sheet for the above study and have had the opportunity to ask questions.
2. I understand that my/ my child's participation is voluntary and that I/he/she is free to withdraw at any time, without giving reason, and without my/his/her speech and language therapy care being affected.
3. I agree to being/ that my child may be **audio-recorded** and that the recordings may be kept for **teaching** purposes.
4. I agree to being/ that my child may be **audio-recorded** and that the recordings may be kept for **research** purposes.
5. I agree to being/that my child may be **video-recorded** and that the recordings may be kept for **teaching** purposes.
6. I agree to being/that my child may be **video-recorded** and that the recordings may be kept for **research** purposes.
7. I agree to having/ that my child may have an EPG palate made and to wear it for recording, therapy (where relevant) and homework purposes.
8. I have/my child has read the consent form and agree to take part in the above study.

Name of Participant	Date	Signature of participant
Name of Participant	Date	Signature of parent / guardian
Name of person taking consent (if different from researcher)	Date	Signature
Researcher	Date	Signature

1 for participant; 1 for researcher; 1 to be kept with speech and language therapy notes

Queen Margaret University College
EDINBURGH

Participant Identification Number:

CONSENT FORM

MRC Research Project: Assessment and Treatment of Impaired Speech Motor Control in Children with Down's syndrome: NORMALLY DEVELOPING CHILDREN

		Please initial box
1.	I confirm that I have read and understood the information sheet for the above study and have had the opportunity to ask questions.	
2.	I understand that my/ my child's participation is voluntary and that I/he/she is free to withdraw at any time, without giving reason.	
3.	I agree to being/ that my child may be **audio-recorded** and that the recordings may be kept for **teaching** purposes.	
4.	I agree to being/ that my child may be **audio-recorded** and that the recordings may be kept for **research** purposes.	
5.	I agree to being/that my child may be **video-recorded** and that the recordings may be kept for **teaching** purposes.	
6.	I agree to being/that my child may be **video-recorded** and that the recordings may be kept for **research** purposes.	
7.	I agree to having/ that my child may have an EPG palate made and to wear it for recording purposes.	
8.	I have/my child has read the consent form and agree/s to take part in the above study.	

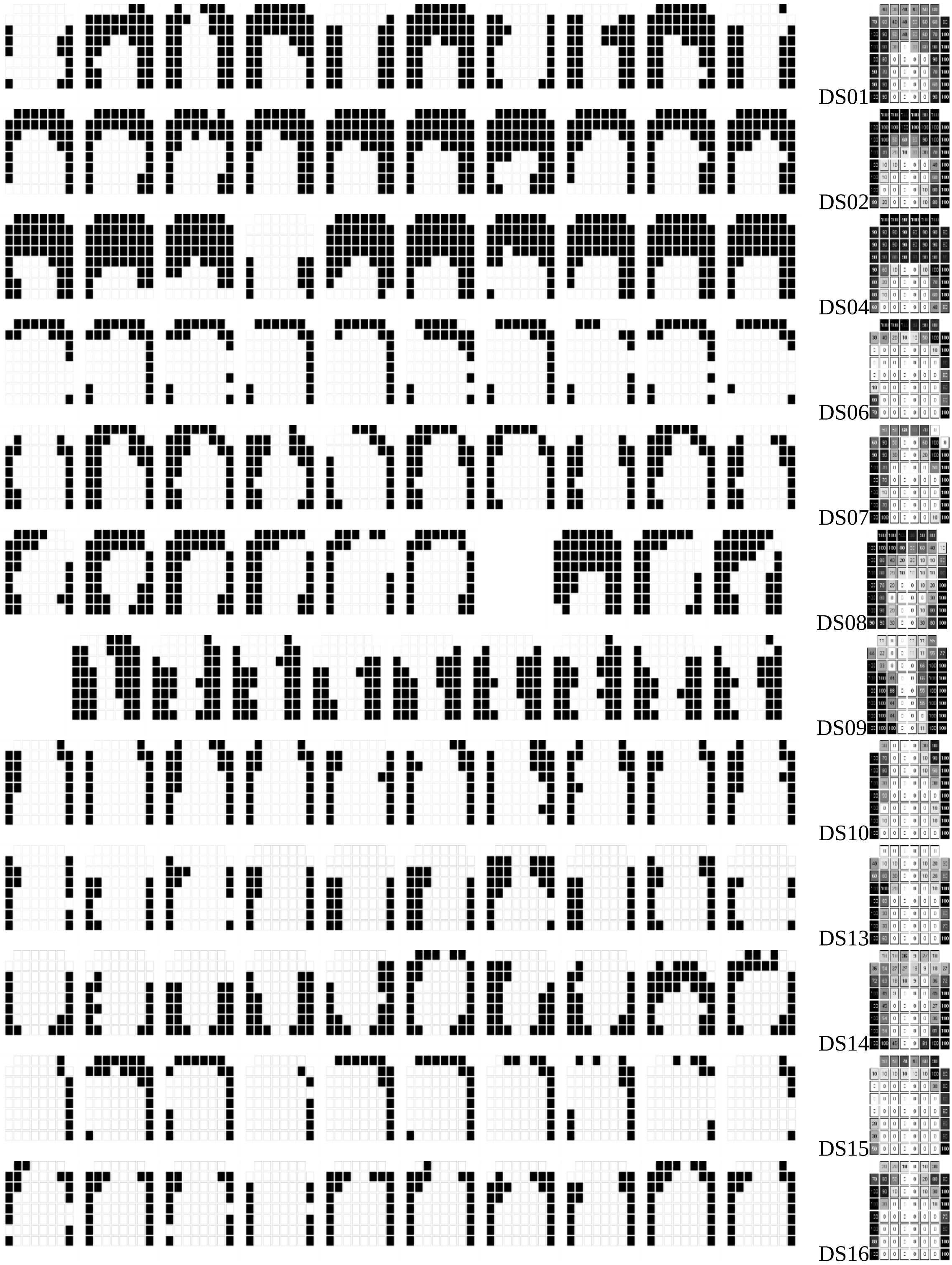
Name of Participant	Date	Signature of participant
Name of Participant	Date	Signature of parent/guardian
Name of person taking consent	Date	Signature
Researcher	Date	Signature

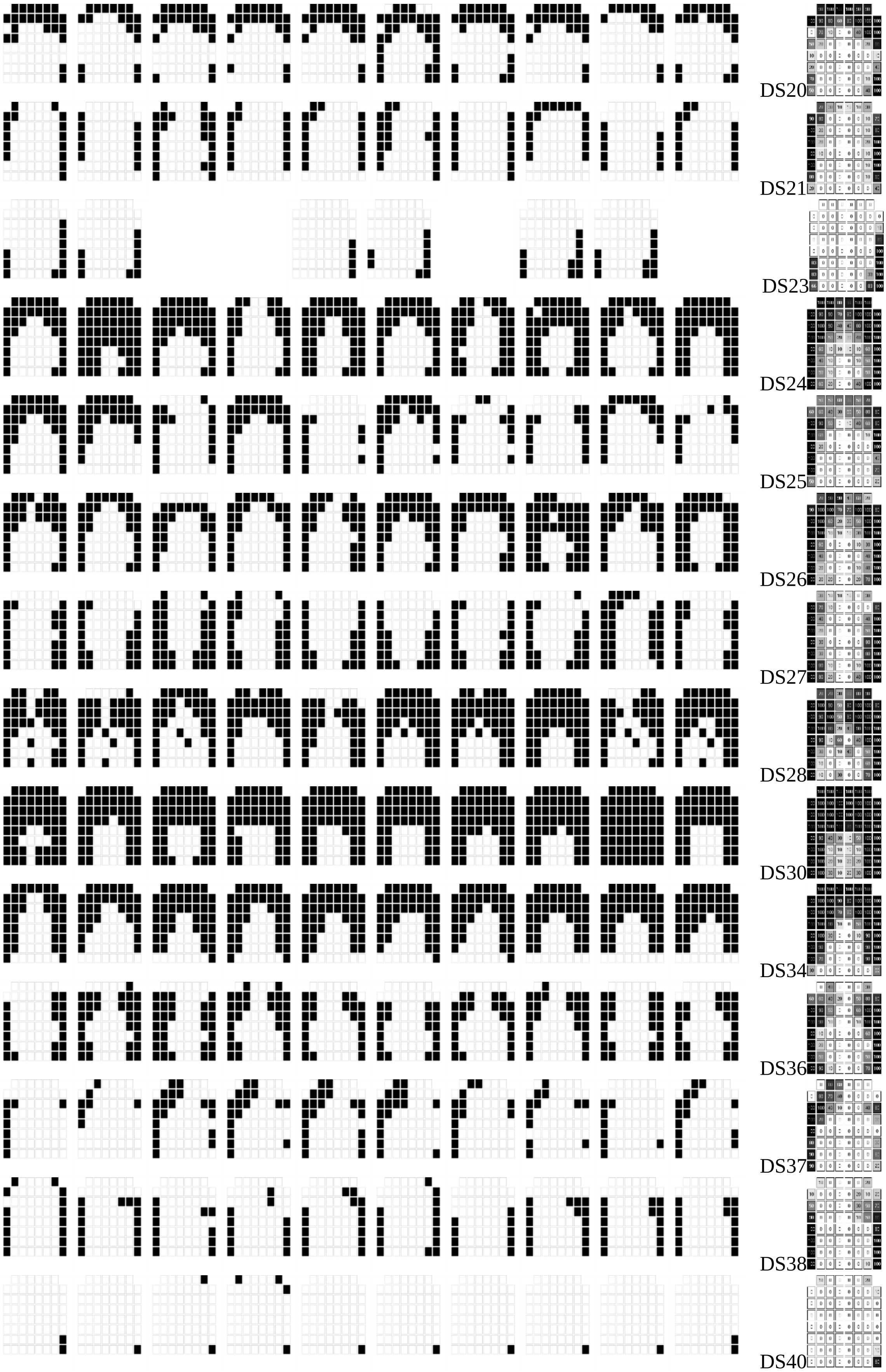
1 for participant; 1 for researcher; 1 to be kept with speech and language therapy notes

Appendix III: EPG frames of maximum constriction

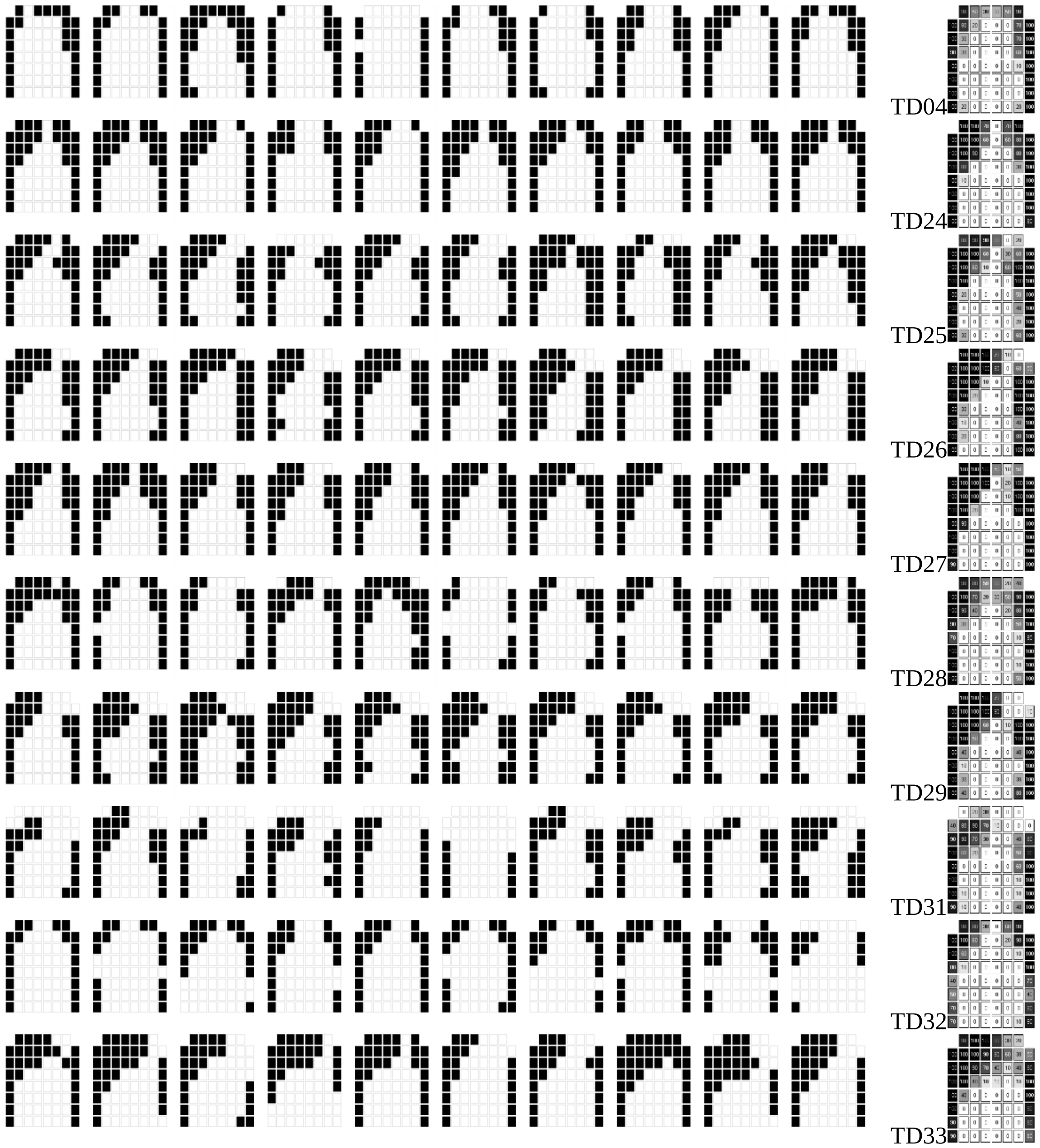
/s/

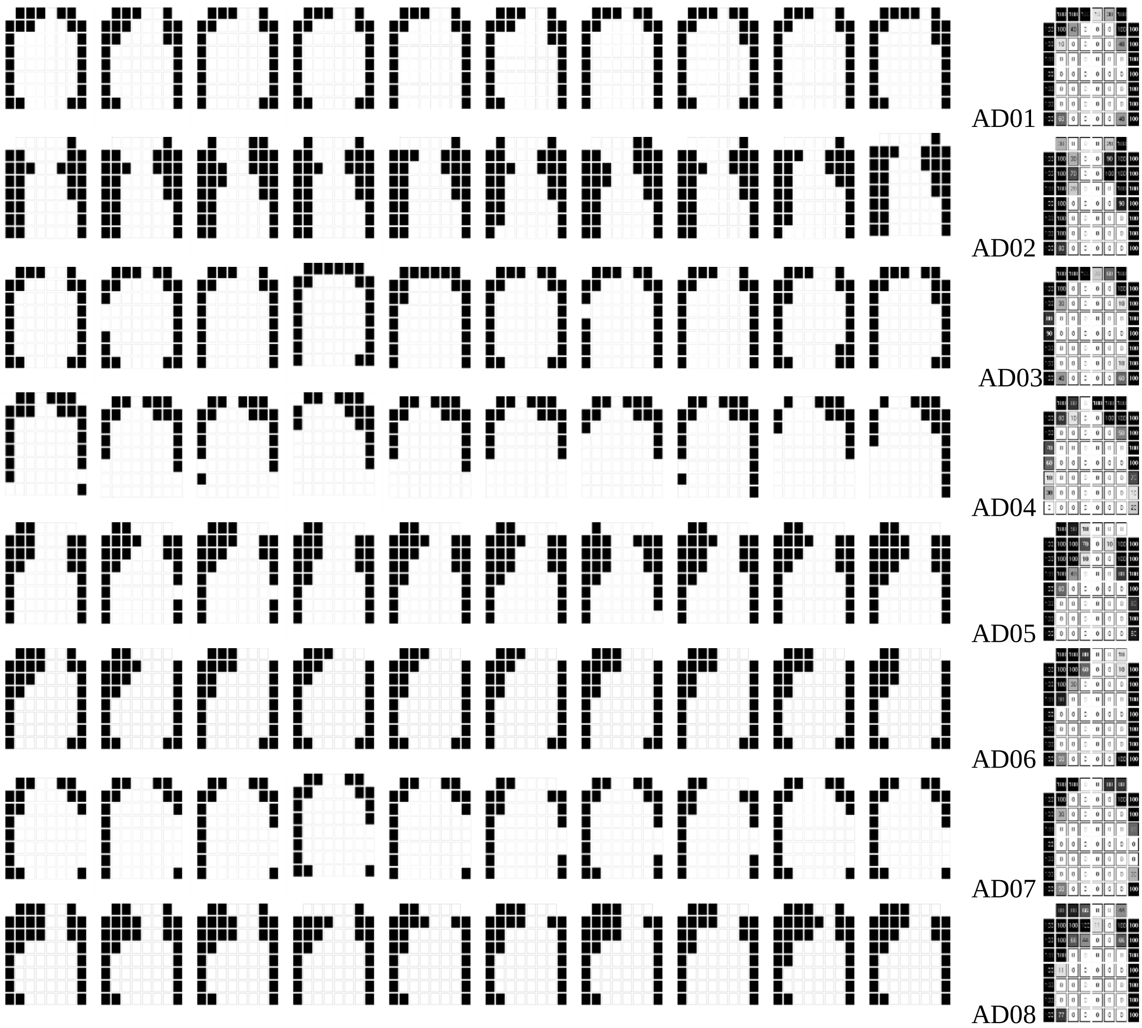
DS group: frames of maximum constriction of all productions and composite frame




DS20
DS21
DS23
DS24
DS25
DS26
DS27
DS28
DS30
DS34
DS36
DS37
DS38
DS40

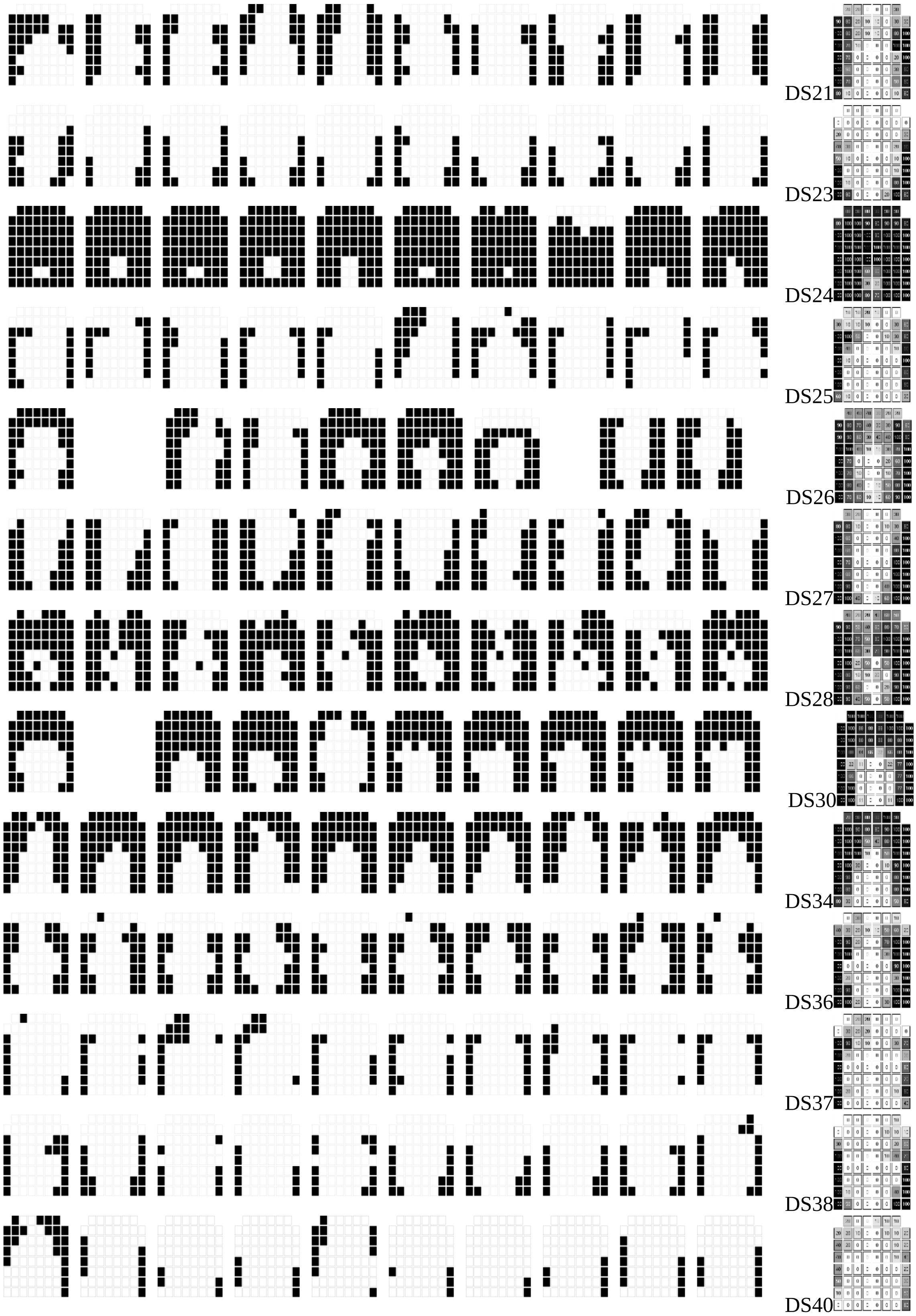
TD group: frames of maximum constriction of all productions and composite frame




AD01
AD02
AD03
AD04
AD05
AD06
AD07
AD08

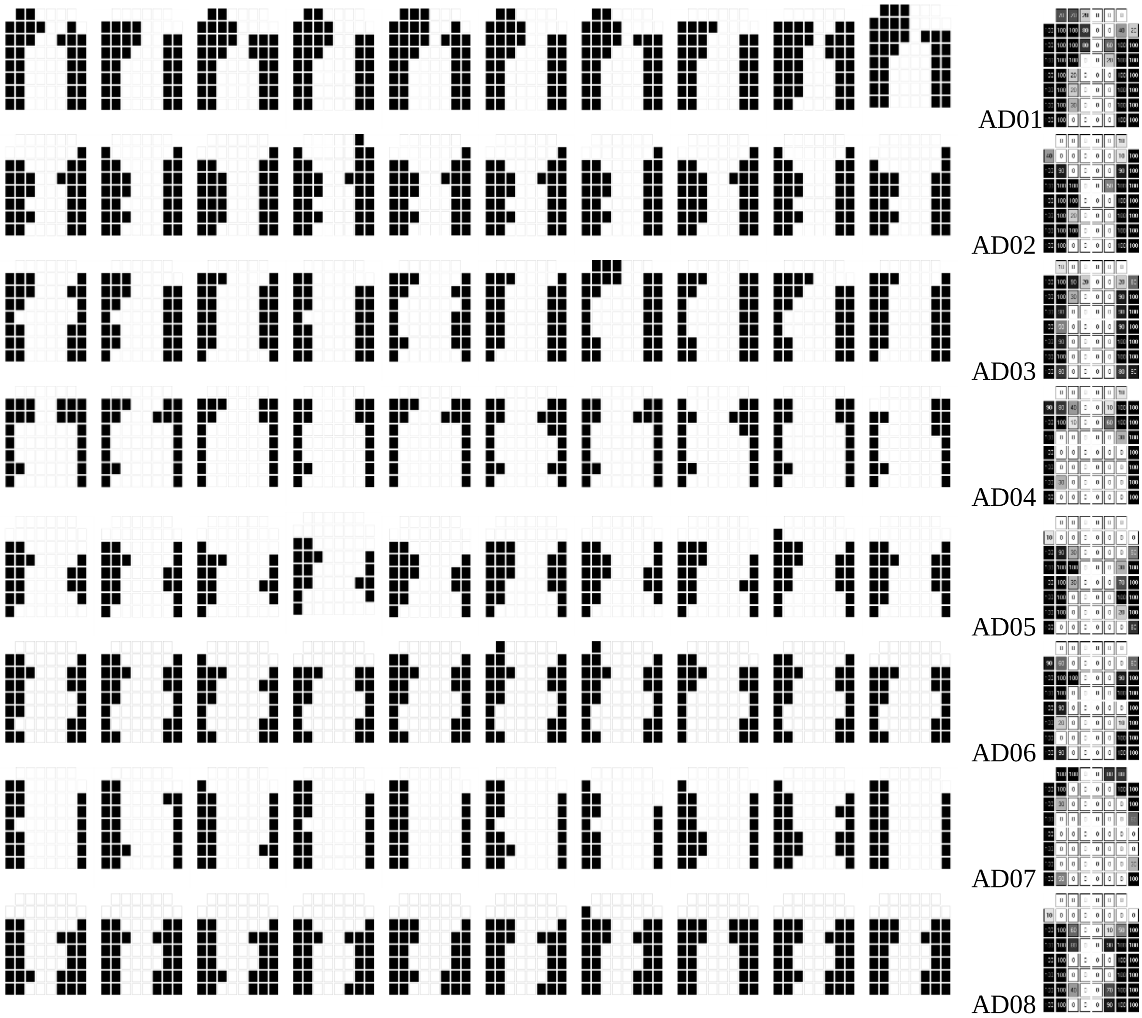
/ʃ/

DS group: frames of maximum constriction of all productions and composite frame


DS21
DS23
DS24
DS25
DS26
DS27
DS28
DS30
DS34
DS36
DS37
DS38
DS40

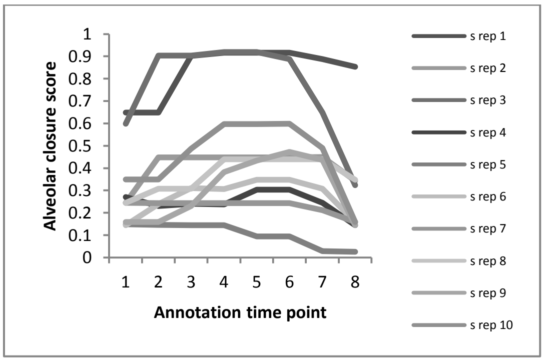
TD group: frames of maximum constriction of all productions and composite frame

AD group: frames of maximum constriction of all productions and composite frame

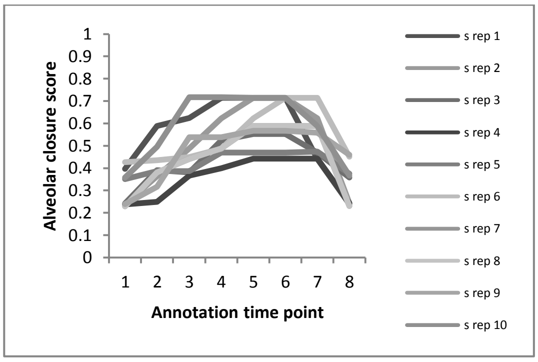


Appendix IV: Alveolar closure scores for typical group

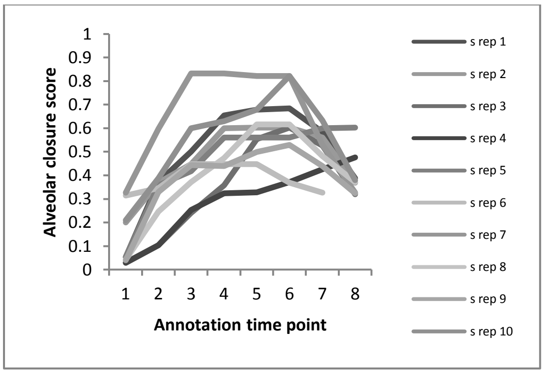
Alveolar closure scores for TD /s/ productions



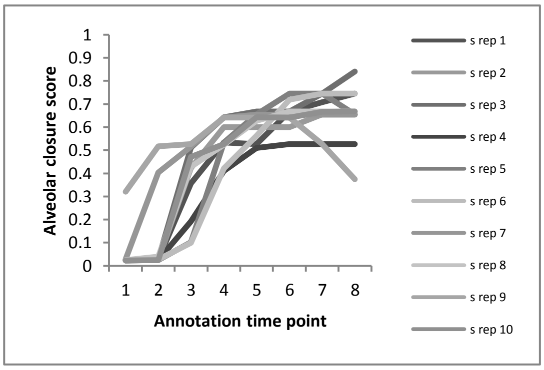
TD04 /s/



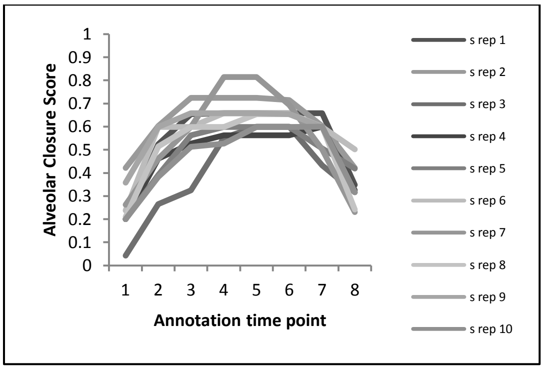
TD24 /s/



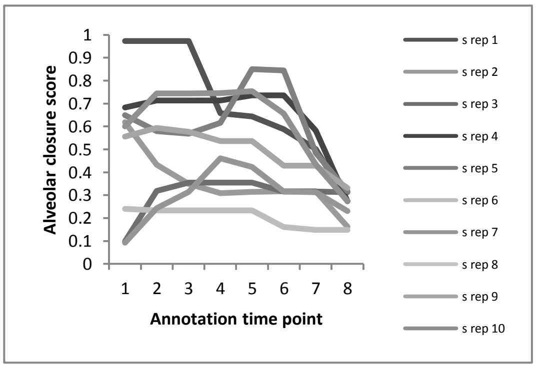
TD25 /s/



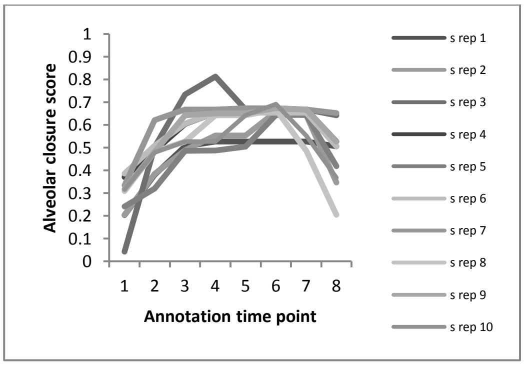
TD26 /s/

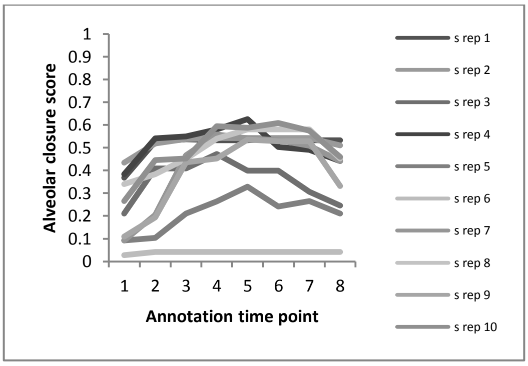


TD27 /s/



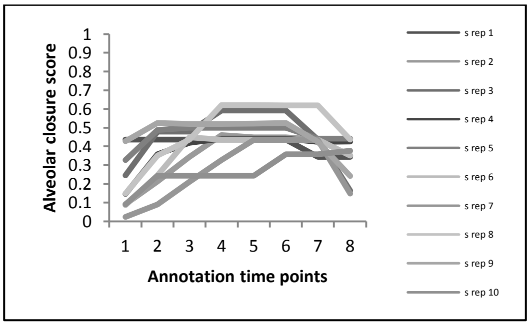
TD28 /s/

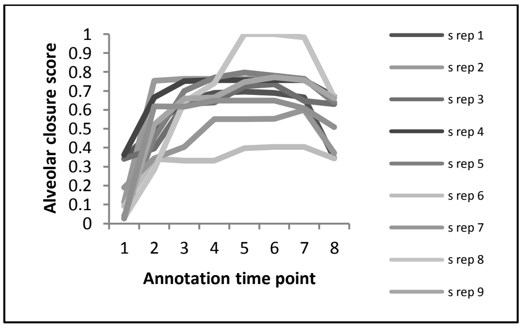




TD29 /s/

TD32 /s/

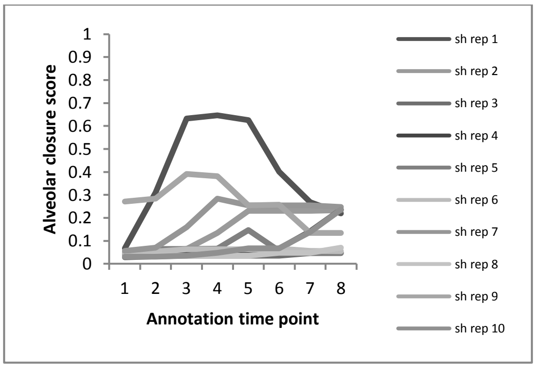


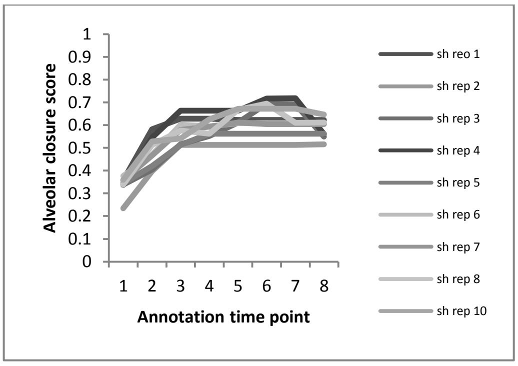


TD32 /s/

TD33 /s/

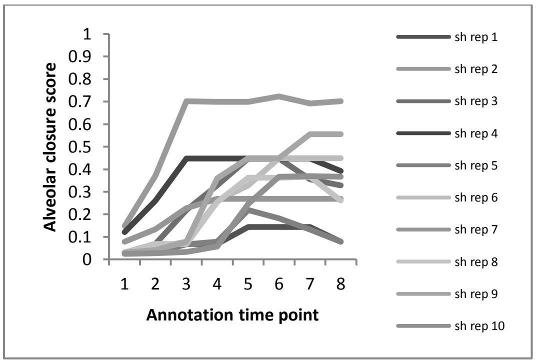
Alveolar closure scores for TD /ʃ/ productions



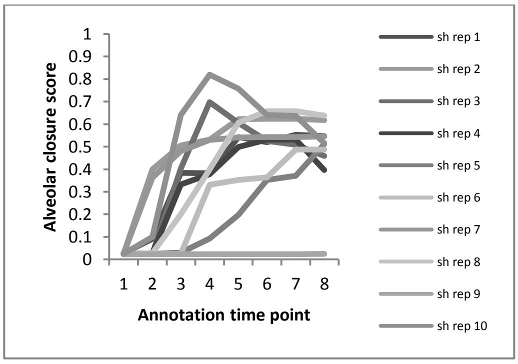


TD04 /ʃ/

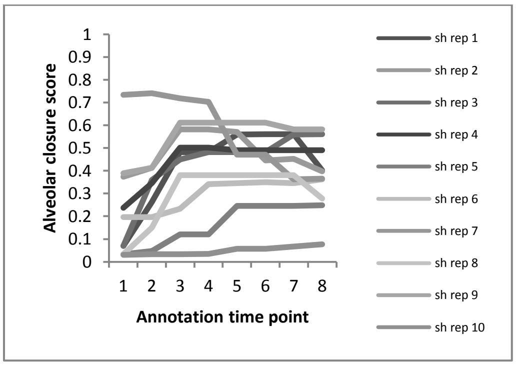
TD24 /ʃ/



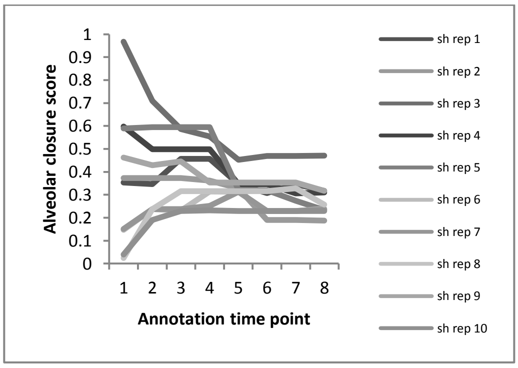
TD25 /ʃ/



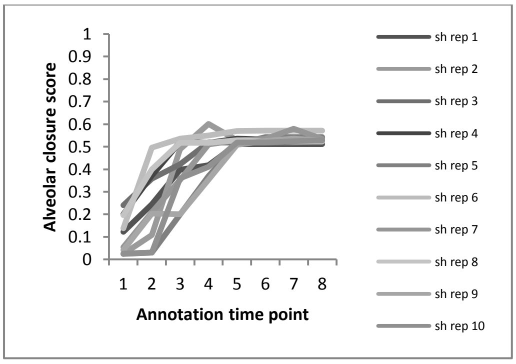
TD26 /ʃ/



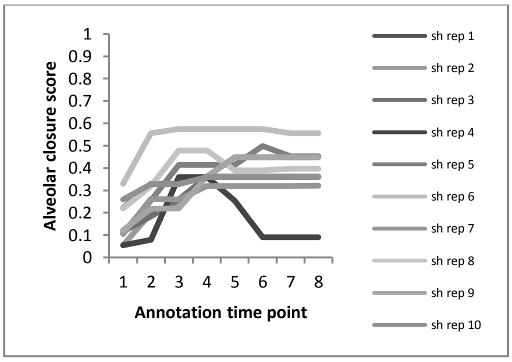
TD27 /ʃ/



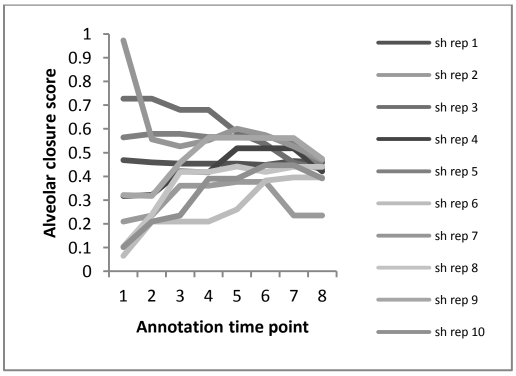
TD28 /ʃ/



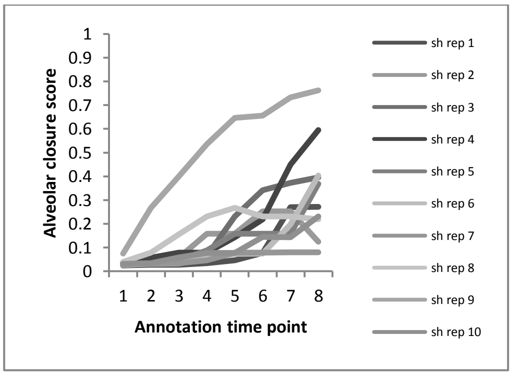
TD29 /ʃ/



TD31 /ʃ/



TD32 /ʃ/



TD33 /ʃ/

Appendix V: Participants dental impressions

Dental Impressions from TD27 (age 7;1) and TD26 (age 5;10)

Dental Impressions from DS01 (age 11;7) and DS30 (age 9;6)

Dental Impressions from DS10 (age 13;10) and DS15 (age 18;9)